

RIGID CERAMIC FILTERS

Numerical Simulation of The Pressure & Velocity Distributions

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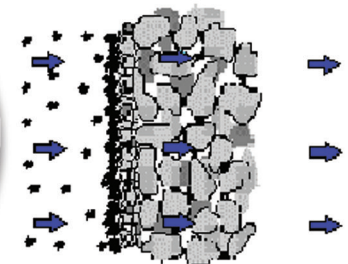
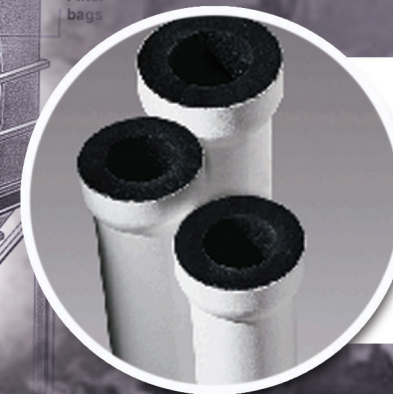
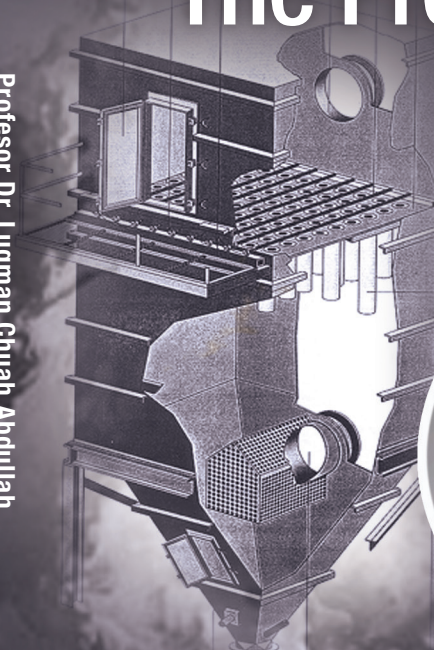
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**Numerical Simulation of
The Pressure & Velocity
Distributions**



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Numerical Simulation of The Pressure & Velocity Distributions

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ABSTRACT

Tightened environmental legislation enacted as a result of government policy has compelled the industry to pay serious attention to air pollution issues. Gas cleaning with ceramic filters has proven to be a major technology for removal of particulate emissions at high temperatures. Filters, after a certain period of filtration time, must be cleaned for maximum efficiency. This can be done by applying a pulsed reverse cleaning flow into the filters. The cleaning mechanisms by which the deposited cake is removed from the filter surface are still not fully understood. Varied mathematical models were thus developed to investigate the flow dynamics of the filtration and reverse pulse flow cleaning in a ceramic filter. These include a Computational Fluid Dynamics (CFD) model, a Simple Excel Reverse Pulse Flow Model and a time-dependent filter cake model. The simulation results were validated using the results of previously reported experiments carried out for filtration and reverse flow cleaning using the filter elements.

NEEDS OF HIGH TEMPERATURE GAS CLEANING

INTRODUCTION

Many industrial processes involve the generation of hot gases, which can be contaminated either with solid, liquid or gaseous pollutants. Environmental legislation enacted as a result of government policy has compelled the industrial sector to pay serious attention to the air pollution issue (LuqmanChuah and Tan, 2013, 2014). With the advent of the Environmental Protection Act, 1990 (EPA90), industrial processes must meet tough emission standards for pollutants. Particulate emission limits for a variety of processes are shown in Table 1. High-temperature, high-pressure particle control is essential to meet both environmental and turbine equipment specifications in advanced coal-fired power generation systems. Thus, attention has been focused on the removal of the particulate emissions, the most visible sign of pollution.

AIR POLLUTION PROBLEM AND LEGISLATION IN MALAYSIA

Malaysia has a great potential market for hot gas cleaning technology. The country has made great strides in economic development during the last two decades. It is endowed with rich natural resources, such as oil and gas, which provide the nation's energy requirements and feedstock for the development of manufacturing and industry. Although Malaysia can be considered as one of the least polluted urban environments in Asia, rapid urbanization and sustained economic growth together with the high demand for transportation has contributed towards air pollution issues (Lim et al., 2008, Tan et al, 2011). With the shift in the nation's strategy from that of

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Table 1 Particulate emission limits for various chemical and combustion industries in England and Wales (after Stephen et al. 1996)

Process		Uk Particulate Release To Air Limit(Mgm-3)
Power Generation		
Coal	20-50MW	300
Oil	<0.4MW	Free from visible
Gas	20-50MW	5
Chemical Processes		
Non-ferrous metal recovery from scrap		50
Iron, Steel and non ferrous foundry		50
Aluminium and aluminium alloy processes		50
Zinc and zinc alloy processes		50
Copper and copper alloy processes		50
Blending, packaging, loading and the use of bulk cement		100
Glass manufacturing processes (All glass types)		100
Coal, coke and coal product processes		50
Incineration Processes		
Sewage sludge		20
<1 tonne hr-1		100
Chemical waste		20
Clinical waste		30
<1 tonne hr-1		100
Municipal waste		30
<1 tonne hr-1		200
Animal carcass		100
<1 tonne hr-1		100
Cremation	80	

agriculture towards manufacturing and heavy industries, a rapid increase in the generation of pollutants and wastes, which will result in the deterioration of air and water quality, is foreseen. The goal of the country to achieve industrial country status by the year 2020 and the associated industrial and urban expansion will further strain the environment in Malaysia.

This section is focused on the air pollution problem and legislation in Malaysia. The problem of air pollution is particularly critical in urban industrial areas like Klang Valley (Luqman Chuah and Tan, 2013, 2014). The deteriorating state of the air quality in this area has been due to the presence of suspended particulates or dust generated by disposal of industrial, municipal and agricultural waste through open burning (Luqman Chuah et al., 2007, Wu Ping et al., 2009). The problem is further worsened by the emissions from power generation plants and industrial combustion.

Table 2 shows some potentially significant air pollution sources published by the Department of Environment, Malaysia (DOE) in 1996. The major air pollutants measured under this air quality monitoring program include suspended particulates, sulfur dioxide, carbon monoxide, nitrogen oxides, hydrocarbons, ozone and lead

Ambient Air Quality Standards have been set as a measure of air quality to ensure that the levels of air pollutants are at safe levels. These standards have been identified for 8 major pollutant parameters, including total suspended particulates, particulates less than 10 microns in size (PM₁₀), dustfall, lead, sulfur dioxide, nitrogen dioxide, carbon dioxide and ozone (Sara et al, 2010; Tan et al, 2011). The standards given are guideline standards for ambient air quality recommended for adoption in Malaysia for the protection of human health and the environment.

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Table 2 Potentially Significant Air Pollution Sources in Malaysia, 1996
(DOE, Malaysia)

Type of sources	Number of Sources				
	1990	1991	1992	1993	1994
a. Chemical Industries					
• Pesticides and Fertilizer	5	5	5	91	80
• Chemical Manufacturing	192	194	175	98	124
• Plastic and Resin	90	91	142	54	53
• Soap and Detergents	9	9	24	69	32
b. Food and Agriculture					
• Palm Oil Mill	260	258	267	286	286
• Rubber Mill	211	209	184	184	168
• Rubber Product Manufacturing	82	91	322	595	594
c. Metal Industries					
• Aluminium Works	19	19	34	34	39
• Foundries	277	261	314	314	228
• Iron and Steel Mill	24	24	26	26	51
• Lead Smelter and Related Works	11	11	32	32	49
• Tin Smelting	5	5	5	5	8
d. Mineral Products					
• Asbestos Works	5	5	5	8	10
• Cerment Products	178	180	185	306	313
• Glass Works	27	27	39	52	219
• Portland Cement Manufacturing	5	5	5	47	47
e. Petroleum Industry					
• Petroleum Refineries	5	5	5	8	46
• Miscellaneous Petroleum Process	28	32	36	36	12
• Gas Processing	24	25	25	30	36
f. Fuel Combustion Sources					
• Thermal Power Station	14	14	14	32	32
• Boiler and Furnaces	2374	2526	2613	2828	2841
• Incinerator	250	279	406	427	448

The Environmental Quality (Clean Air) Regulation, 1978, is applied mainly to the regulation of air emissions from industrial facilities and other point sources of air emissions. The regulations, enforced since 1 October, 1978, specify the permissible limits for air emissions which have to be complied with. These air emission limits are applicable to any source or for specific sources or activities, as outlined in Table 3. All existing plants were required to comply with Standard A within two years and Standard B within 3 years, whilst all new plants must comply with Standard C which is the most stringent.

Table 3 Environmental Quality (Clean Air) Regulation, 1978.
(DOE, Malaysia)

Substances Emitted	Standards		
1. Solid particle concentration in the heating of metals.	Standard A: 0.3 g/m ³ Standard B: 0.25 g/m ³ Standard C: 0.2 g/m ³		
2. Solid particle concentration in other operations.	Standard A: 0.6 g/m ³ Standard B: 0.5 g/m ³		
3. Metals and metallic compounds:	Standard C: 0.4 g/m ³		
	Std. A	Std. B	Std. C (g/m ³)
• Mercury	0.02	0.01	0.01
• Cadmium	0.025	0.015	0.015
• Lead	0.04	0.025	0.025
• Antimony	0.04	0.025	0.025
• Arsenic	0.04	0.025	0.025
• Zinc	0.15	0.1	0.1
• Copper	0.15	0.1	0.1

APPLICATION OF CERAMIC FILTERS AS HIGH TEMPERATURE SEPARATION DEVICES

The frontier in gas filtration is removing particulates from gases at elevated temperatures. In chemical and process industries and in incineration, the need for gas cleaning is increasingly being driven by the requirements of environmental legislation, which is directed specifically at particulate, acid gases, heavy metal compounds, hydrogen chloride and organic chlorides, such as dioxin and furans.

Several economic and technical considerations have made hot gas cleaning preferable to cold gases. This is because certain industrial processes could be corrosive if they are operated below acid dew points which will cause damage to the operating units. High temperatures must thus be maintained for those processes. Filtering at higher temperature not only helps to prevent the corrosion problem but may also improve both thermodynamic efficiency and versatility of the overall process. Moreover, with the corresponding reduction in the total power requirement due to the lower pressure drop, it is more economical to filter gases hot instead of cold.

Table 2 gives some examples of applications of hot gas cleaning and their operating requirements. The first group comprises three distinct types of systems for electrical power generation from coal, all of which have their own requirements for gas cleaning at high temperatures.

CERAMIC FILTERS IN HIGH TEMPERATURE GAS CLEANING

The need for hot gas filtration is driven by the social pressure for environmental clean up under the tighter legislation of the Environmental Protection Act, 1990. This Act came into force in

April, 1991, and imposes restrictions on the operations of many industrial processes (Chuah, 2003). The U.K. pioneered the concept of Integrated Pollution Control (IPC), when it introduced the system in EPA90 and the idea is now realised at local community level following the adoption of the Integrated Pollution Prevention Control (IPPC) Directive. Under this Act, industries with the greatest potential to pollute the environment are subjected to Integrated Pollution Control (IPC) systems regulated by the Environment Agency.

The enforced cleaning of these gases is providing opportunities for ceramic filters to demonstrate their capabilities. The IPC system requires that certain identified processes must use the “Best Available Techniques Not Entailing Excessive Cost” (BATNEEC) criteria to prevent the release of particular substances to the environment. The options available to achieve this goal are limited. Essentially, the traditional hot gas technologies are bag filters incorporating fabric filter media, cyclones, electrostatic precipitators and wet scrubbers. With fabric filters and wet scrubbers, cooling of the gas stream is essential and maximum efficiency is thus linked to maintaining the gas temperature within a narrow band. Further, cyclones, wet scrubbers and electrostatic precipitators are becoming less attractive with the tightening of emission limits, which favors more efficient barrier filtration techniques. The objectives of developing new hot gas cleaning technologies are to provide high efficiency, high-reliability, cost-competitive and environmentally superior processes, as compared to the conventional methods. Hence, the development of hot gas clean up technologies has tended towards producing a barrier type filter, capable of meeting the ever decreasing limits for particulate emissions and free from the restrictions of temperature excursion vulnerability. For particulate emissions control, the Environment Act, 1990, has designated ceramic filters

Rigid Ceramic Filters

Table 4 Summary of potential high temperature gas filter applications and operating requirements. (Chuah, 2000)

Application	Operating Temperature (°C)	Gas Pressure (bar)	Filter Device Environment	Requirements
Power Generation Pressurisedfluidised Bed combustion	800	10	Oxidising with alkali	Turbine protection; meet environmental standards
Integrated Gasification Combined cycle	600-800	10-30	Reducing with Alkali, H ₂ S	Turbine protection; meet environmental standards; protect sulphur capture beds
Conventional	<700	1	Oxidising	meet environmental standards; low ΔP
Chemical process Metal refining Calcination/drying Catalytic cracking Precious metal Recovery	300-750	1-3	Varied, can severe	Enhanced product recovery; reduced environmental emissions; resource recovery; energy recovery
Incineration Hazardous waste Municipal waste Kiln furnaces	up to 1000	1	Oxidising, Containing reactive chemical species	Reduce environmental emissions; Improved incineration process; protect downstream equipment

a BATNEEC for many processes. It is clear that there is thus a large potential market for rigid ceramic filters. Table 4 shows some of the potential high temperature gas filter applications.

RIGID CERAMIC FILTERS

Requirements for an effective high temperature filter medium are that it must be resistant to chemical and thermal attack and sufficiently porous so as not to offer an unacceptably high resistance to flow, but not so porous as to allow appreciable particle ingress or “penetration” into the structure. A rigid ceramic filter is an effective gas filtration device that is designed to remove particles from gases at high temperature (Figure 1). Rigid ceramic filters were first utilised in both combustion and gasification of coal for environmentally clean power generation in the early 1980s. Direct application of high-temperature particulate control ceramic filters is expected not only to be beneficial to advanced fossil fuel processing technology, but also to selected high temperature industrial and waste incineration processes.

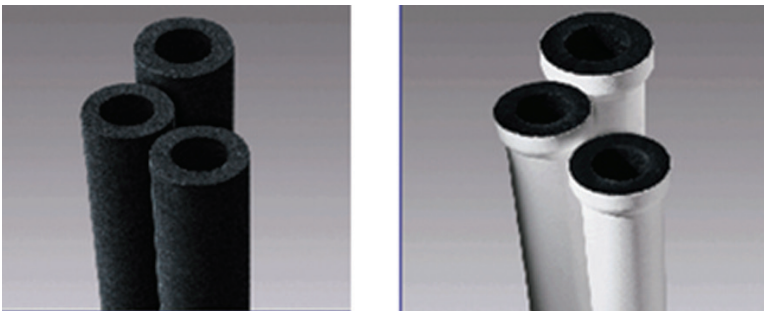


Figure 1 Ceramic filters (Chuah, 2000)

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Ceramic filters are designed to meet performance, life and cost constraints of the process applications in which they are used. They have proven to provide a highly effective high-temperature filtration method that possesses excellent resistance to chemical and thermal attack. Ceramic filters have also demonstrated strength in high particulate removal efficiencies, high flow capability and relatively low pressure drop characteristics.

Basically, there are two types of rigid filters which are commonly used: dense granular media and low density media. Dense granular media filters are usually formed from ceramic granules with an intergranular void fraction of the order of 30 to 50%, whilst low density media filters are formed from ceramic fibres with a void fraction of the order of 80-95%. Dense media are generally used in power generation applications, whilst low density media are commonly found in the chemical and process industries.

Owing to the difference in the void fraction between the two types of medium, it is not surprising that the resistance to flow of an unused filter element of the low density ceramic filter is usually considerably less than that of a granular ceramic element of similar filtration performance. However, commercially available granular media filters have now been improved and have better resistance to dust penetration without too great an increase in pressure drop.

The principal factors which limit the life of ceramic filter materials can be summarized as follow:

- Reaction of gas phase alkali and/or steam with the amorphous glass or binder phases;
- Oxidation of non-oxide-based ceramics;
- Phase transitions;
- Thermal shock during pulse cleaning or system transients;
- and

- Mechanical shock and degradation in handling/depletion of the binder phase.

CROSS-FLOW CERAMIC FILTERS

Westinghouse Corporation has developed a compact hot gas particulate cleanup system known as the cross-flow filter, which can operate at high temperatures (650 to 900°C), whilst removing coal ash and spent sorbent particles from turbine inlet gases (Seville et al., 2000). As the filter accomplishes virtually complete particulate removal it also provides compliance with particulate air emission standards, thereby negating the need for a downstream cold-end electrostatic precipitator or fabric filter.

The development of the cross-flow filter technology has evolved steadily through the stages of initial exploratory studies to pilot scale tests at various bench scale gasification and combustion plants, such as the test in the Texaco gasifier at Montebello, California. The technology development activity has been focused on long-term material stability, the mechanical design aspects of the overall system and the operational requirements for integration with a prototypical gasifier or combustor. Figure 2 illustrates the Westinghouse cross-flow filter's compact, modular design.

OTHER HOT GAS CLEANING TECHNOLOGIES

There are several other hot gas cleaning technologies available currently. These include cyclones, wet collectors (gas washers), fabric collectors and electrostatic particulators.

CYCLONES

A cyclone is an inertial separator. It is simple and inexpensive to make, relatively economical to operate and adaptable to a wide range of operating conditions. Cyclones rely on a change in direction of

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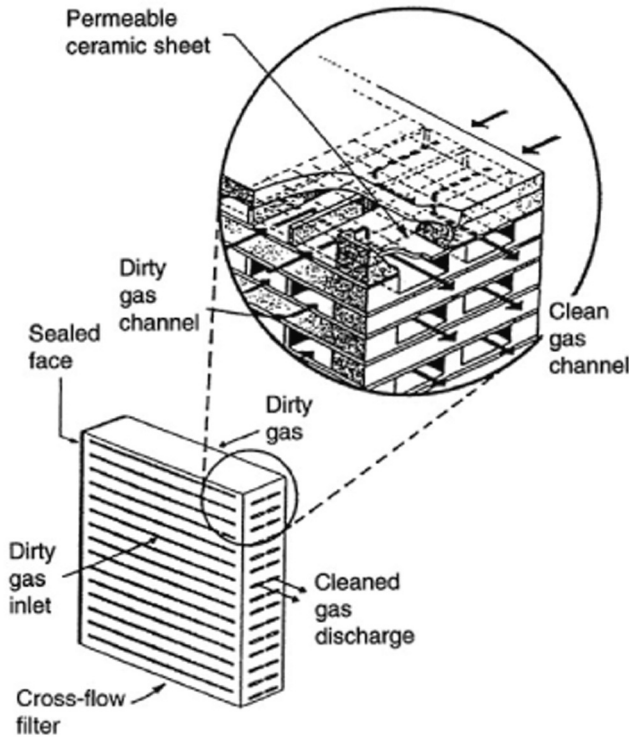


Figure 2 Schematic of the Westinghouse cross-flow filter
(Ciliberti and Lippert, 1986)

the gas stream to collect material on a surface. A gas that enters the cyclone undergoes some kind of vortex motion forcing particles either to accumulate into a small part of the gas flow or to be separated by impingement onto a surface (Figure 3). Several designs of cyclones exist for gas cleaning purposes. Reverse-flow cyclones are amongst the most common cyclones used in industry. Cyclones can handle heavy loads with the capacity range 200 - 85,000 m³/hr. These collectors can be made to withstand high temperatures of up to 1000°C and high pressures, and the only limit is the softening point of the material used to construct the device.

PROCESS CYCLONE SCHEMATIC

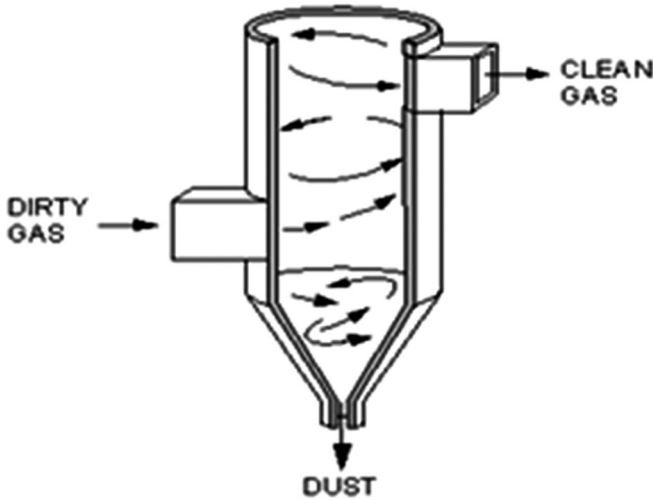


Figure 3 Schematic diagram of cyclone (Chuah and Mohd Halim, 2013)

Cyclone designs are inefficient for collecting particles smaller than about 5 microns. However, high efficiency cyclones used in parallel or in series can collect particles of between 2 and 5 microns (Jolius and Luqman Chuah, 2010). The volume capacity is a function of the unit's diameter. The smaller the diameter of the cyclone, the higher its collection efficiency of smaller particles. This has resulted in a series of designs where multiple small cyclones are packaged together to achieve higher volumes (Chuah and Mohd Halim, 2010).

A practical problem of cyclones, that can be foreseen, is maintaining a constant discharge rate of the collected particles from the cyclone. If blockage of the solid discharge does occur in a cyclone used for turbine protection in a power generation plant, the turbine can be damaged by the highly concentrated particles

long before the problem is detected. In practice, the cyclones used in power generation plants tend to use two stages of cyclones accompanied by a barrier filter.

ELECTROSTATIC PRECIPITATORS

Electrostatic precipitators (EPs) are commonly used for collection of solids from gas streams. They are used for the removal of solid contaminants from process gases or dedusting dry offgas from industrial processes in the temperature range 100 – 450°C. The collection process relies on electrostatic charging of the particles and subsequent accumulation of the charged material onto collection surfaces in the gas stream.

The device consists of a series of voltage electrodes and collector electrodes. The collecting electrodes are parallel vertical plates (Figure 4). These form passages, in the center of which the discharge electrodes are suspended from insulators. The plates are shaped to provide quiescent zones to prevent the collected dust from being stirred up and re-entrained by the gas stream.

Particles are charged and separated from the gas stream under the influence of the electric field generated between the electrodes. The efficiency of an EP is directly related to the dust concentration, collector area, migrational velocity and indirectly related to the gas flow rate.

The EPs have three basic stages:

1. Electrical charging of the suspended particulates;
2. Collection of the charged particulates on a grounded surface; and
3. Removal of the particulates from the collecting surface by mechanical vibration (rapping) or flushing with liquids.

EPs benefit from low operating costs and operate with a relatively low-pressure drop. However, their space requirement is high, and so is the initial capital cost. EPs are not suitable for applications where gas flow rates and process conditions are variable.

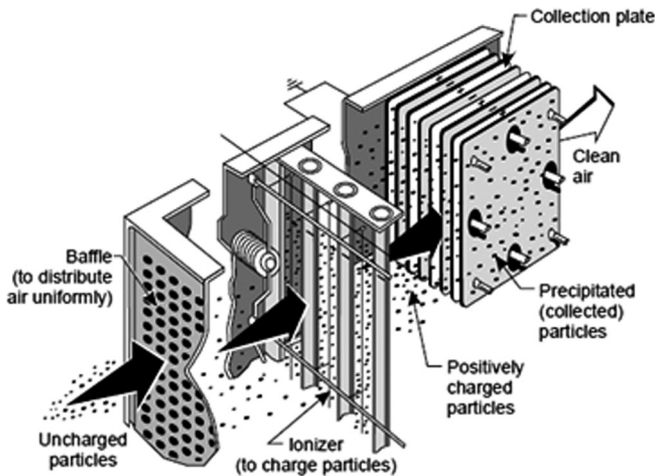


Figure 4 An electrostatic precipitator (Chuah and Mohd Halim, 2010)

WET SCRUBBERS

Scrubbing refers to the process of removing solid or liquid particulates from a gas stream by contact with a liquid drop. In scrubbers, most particles will adhere to the liquid drop if they come into contact with it. The absorbing liquid and all of the particulates must then be separated and removed from the carrier gases.

Wet scrubbing is a mature technology which is widely applied to the collection of soluble gaseous species and particulate material (Figure 5). Wet scrubbers rely on intimate contact of the flue gas stream with the scrubbing liquor to achieve collection of the pollutant gases and particulates. Different designs of wet scrubbers

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include: packed bed scrubbers, moving bed scrubbers, plate column scrubbers, venturi scrubbers, condensation scrubbers and foam scrubbers.

The flue gas passes through the scrubbing vessels and contacts with the flow of scrubbing liquor. The liquor wets, dissolves and entrains the gaseous and solid pollutants which then leave in the liquor phase out of the bottom of the scrubber, whilst the cleaned flue gas exits via a separate conduit.

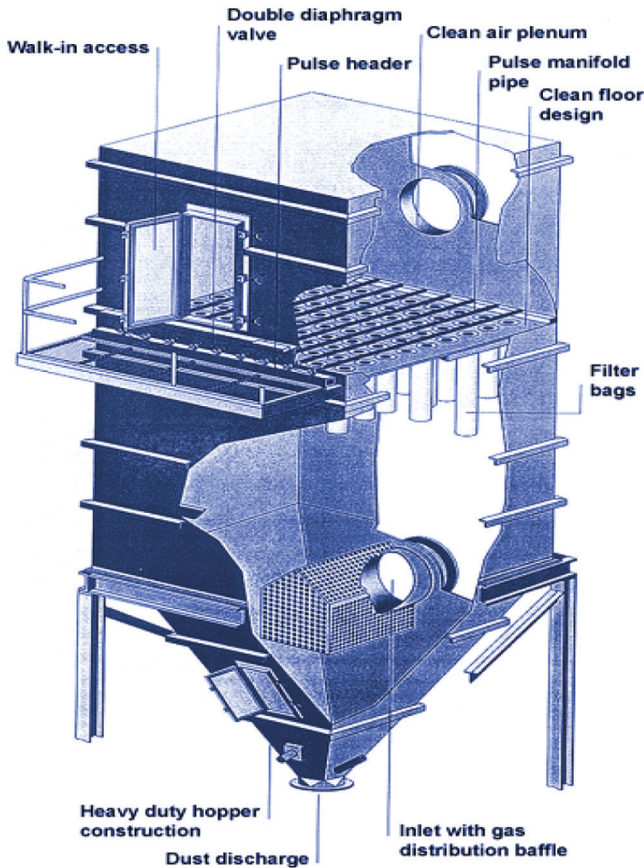


Figure 5 Wet scrubber (Chuah and Mohd Halim, 2010)

Wet scrubbers have the advantages of being able to handle hot gases, sticky particles and liquids. Their disadvantages are however, that they require higher energy consumption, discharge wet gases and produce a wet product, which then has to undergo effluent treatment. All wet scrubbers rely on the scrubbing liquor, usually water, but can include dilute solutions of low cost bulk chemicals, e.g. alkalis (when scrubbing acid gases).

Current developments relate mainly to customizing the scrubber type, liquor type, packing type or plate arrangement and operating regimes for particular applications as well as integration into the total gas cleaning system.

FABRIC FILTERS

Fabric filters, commonly known as “bag filters”, are collectors where dust is removed from the gas by passing the dirty gas stream through a woven or felted filter bag. The dirty gas being cleaned is usually drawn through the bags by a fan at a predetermined velocity. The bags are cleaned by mechanical shaking, reverse flow or pulse-jet cleaning. Fabric filter technology is well established and can deliver good filtration efficiency (99-99.9%). Its good performance characteristics make fabric filters the preferred choice for conventional gas-cleaning problems and they are thus applied in a wide range of processes. Unfortunately, they are limited in terms of temperature capability and face velocity. Successful installations at temperatures much above 250oC are unusual.

Fabric filter bag houses of standard design are built as modules, which can be operated singly or combined to form larger units (as shown in Figure 6). Custom-designed bag houses are very expensive and used almost exclusively for handling larger volume gas streams.

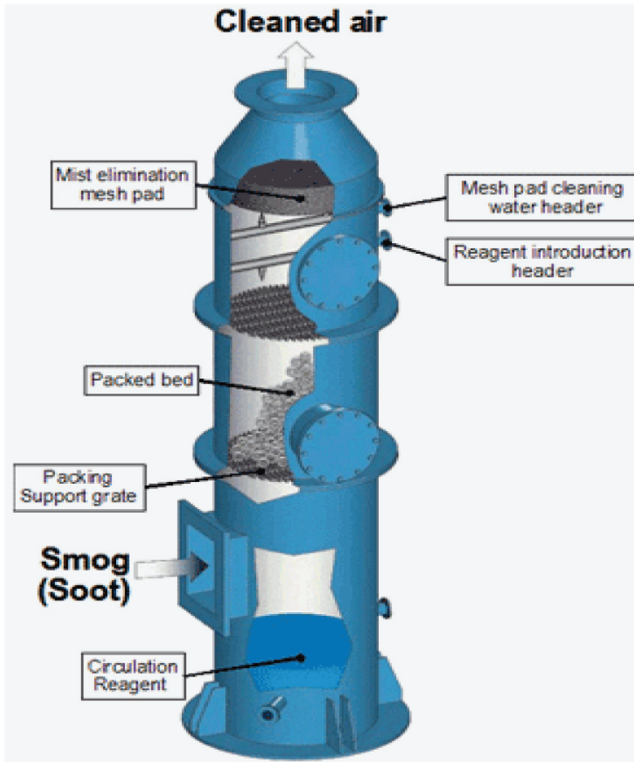


Figure 6 Fabric filter bag housing (Chuah and Mohd Halim, 2010)

GRANULAR BED FILTERS

Granular beds consist of beds of unbonded filter elements, which are typically particles of several hundred micrometres in size of some durable material such as quartz sand. They fall broadly into three categories: fixed beds, moving beds and fluidised beds. In general, they have a higher packing fraction (around 60%) than fabric bed filters. Due to the larger granule size (0.5 mm or more), the filter efficiency is poorer than the fibre-packed bed and the pressure drop is lower. Granular beds were not in favour for a long period of time and only came back into the limelight after the oil

crisis and the resurgence of coal-fired boilers in power generation plants, as high temperature dust collectors. The major advantages of granular beds are:

1. durability at high temperatures, which stems from the use of heat resistant materials, such as sand, ceramics and a variety of metals, as the filter medium;
2. clogging of the filter can be avoided by the use of the moving-bed concept; and
3. granules can be recycled and reused, after removing the accumulated particles by sieving or fluidised beds. It is therefore, possible for a moving bed to maintain stable operations with constant filtration efficiency and pressure drop.

A counter-current moving-bed granular bed filter is shown in Figure 7.

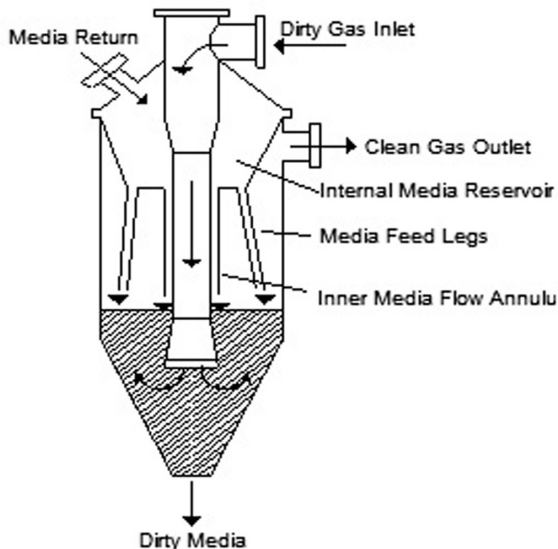


Figure 7 Counter-current moving-bed granular bed filter

METAL FILTERS

The use of metal filters is limited to very specific applications due to their poor corrosion resistance and high cost. The filters are fabricated from woven or felted metal fibres or from sintered powdered metals. Filters made from stainless steels are normally used at operating temperatures up to 600°C, whilst some super alloy materials can be used for higher temperature applications. They are operated in the same way as rigid ceramic filters and bag filters, i.e. the gas flows radially inwards, with a dust cake being deposited on the outer surface of the filter. The cake is removed periodically by reverse pulse cleaning.

Metallic filters are available in fabric and rigid forms. A number of manufacturers, including Michigan Dynamic, Pall and Memtec, offer completely rigid elements, while Bekaert's Bekipor supplies both flexible felt and rigid woven versions. The sintered powdered metal with woven backing version offered by Pall and the sintered metal fabric batt with woven backing offered by Memtec (U.S. Filter), are improved designs of the traditional wire-cloth, since both designs attempt to promote surface filtration. However, it was noticed from an industry study that there have been instances of cracking with the sintered powdered metal element. The advantages of both types of filters are high filtration efficiency, washability, the possibility to weld sections together to form long filter tubes and their ability to withstand higher pressures and temperatures. In-plant testing of the metal filters also shows that the metal filters possess high strength of ductility and high thermal conductivity. The biggest disadvantage of these filters is their cost. However, recently developed metallic membrane elements are said to possess low maintenance and reduced investment cost and also possess good corrosion resistance.

SUMMARY OF HOT GAS FILTRATION METHODS

Hot gas filtration is a key component of current power generation systems that are based on the combustion and gasification of coal, chemical process industry and incineration processes. Effective particulate removal protects downstream heat exchangers and gas turbine components from fouling and erosion while cleaning the gas stream to meet with environmental emission requirements. Conventional gas cleaning technologies are however becoming less preferable with the tightening of emission limits, which favour more efficient barrier filtration techniques. Ceramic barrier filters are the most advanced hot gas filtration technology systems with several systems close to commercialization for use in temperature range up to 1000oC. This section has covered the current available technologies and commercial status of hot gas filtration technologies. An overview of the gas cleaning devices is summarised in Table 3.

HIGH TEMPERATURE GAS CLEANING DEVICES IN POWER GENERATION

Energy sources, particularly coal, have some impact on our environment. Coal for example does substantially more harm than renewable energy sources by most measures, including air pollution, damage to public health and global warming emissions (Aini Mat and Luqman Chuah, 2012). Over the past three decades, significant efforts have been made toward the development of cleaner, more environmentally acceptable, advanced coal-fired power generation technology. In the process the coal gasification technology received a big thrust with the concept of combined cycle power generation. The present emphasis is towards the development of an Integrated Gasification Combined Cycle (IGCC). IGCC has the inherent characteristics of gas clean up, waste minimization and improved

Rigid Ceramic Filters

energy efficiency, which make this system environmentally preferable. Commercial scale demonstration plants and other studies have shown that the flue gas and particulate emissions from an IGCC plant are drastically lower than the permissible emission limit.

Table 5 Overview of devices for particulate removal

Device	Collection Efficiency (%)	Operating Pressure Drop (mbar)	Flow Capacity (m ³ /s per m ²)	Energy Requirements
Cyclones:				
● Conventional	Low (>90)	Moderate to high (75-275)	Very high	Low
● Enhanced	>90	Moderate to high	Very high	Moderate to high
Granular filters	Good (>99)	Moderate (60-100)	High (0.15 to 0.2)	High
Electrostatic precipitators	Good (>99)	Very low (3-6)	Low to moderate (0.01-0.03)	Moderate to high
Fabric filters	Excellent (>99.5)	Moderate to high (75-200)	Moderate to high	Moderate
Rigid barrier filters:				
● Ceramic candle	Excellent (>99.5)	Moderate to high (50-250)	Moderate to high (0.03-0.07)	Moderate
● Cross flow (Westinghouse)	Excellent (>99.5)	Low to moderate (25-75)	Moderate to high (0.03-0.07)	Low to moderate
● Ceramic tube (AGC)	Excellent (>99.5)	Moderate (80-125)	Moderate to high (0.03-0.07)	Moderate

High temperature gas cleaning is an essential component of an IGCC and other advanced coal-fired power generation technologies such as Pressurised Fluidised Bed Combustion (PFBC). In such a process, electricity is generated through the use of both steam and gas turbines. Hot gas filtration systems are designed to protect the gas turbines from particle fouling and erosion. Development of high temperature filters for power generation has progressed steadily over the last decade, with increasingly larger test facilities. A summary

of the main filtration test rig and demonstration plants for both the IGCC and PFBC is shown in Figure 8.

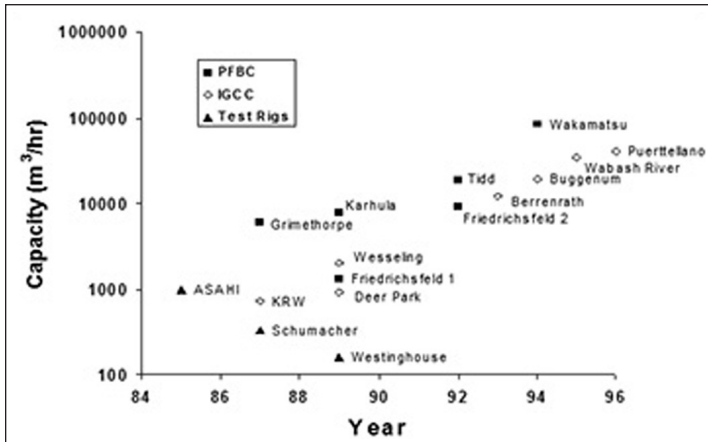


Figure 8 Ceramic Filter Facilities used in Power Generation (after Stephen et al., 1996)

PRESSURISED FLUIDISED BED COMBUSTION

Pressurised Fluidised Bed Combustion (PFBC) technology has been used on a commercial scale in Sweden and Japan, where traded coals are of higher quality than in many other countries. It allows the efficient combustion of coal in an environmentally acceptable manner by reducing the emission of particulates and SO₂ and NO_x.

In a PFBC system, the combustor, hot gas cyclones and even the filters are enclosed in a pressure vessel (Figure 1.9). The PFBC units are intended to give an efficiency value of over 40% and low emissions. Development of the system using more advanced cycles is intended to achieve efficiencies of 40-41% as compared to the approximately 38% of the basic steam cycle. The PFBC units operate at pressures of 10-15 bars with combustion temperatures of

800-900°C. The pressurised coal combustion system heats steam, in conventional heat transfer tubing, and produces a hot gas which is supplied to a gas turbine. Gas cleaning is a vital aspect of the system, as is the ability of the turbine to cope with some residual solids.

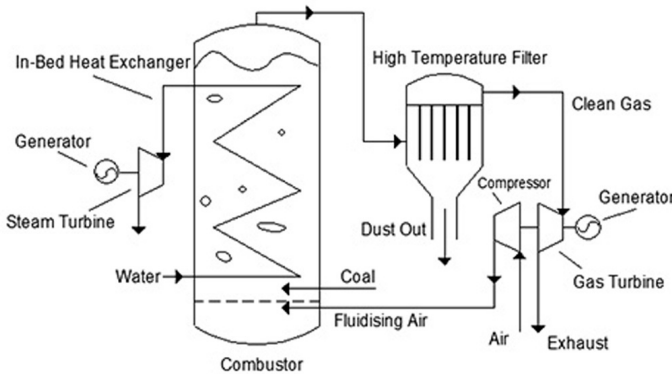


Figure 9 General schematic diagram of a PBFC (Chuah and Mohd Halim, 2010)

INTEGRATED GASIFICATION COMBINED CYCLE

Like the PFBC, this technology is relatively new in connection with power generation. Coal-based Integrated Gasification Combined Cycle (IGCC) plants for power generation passed through a critical stage in their development during the 1990s.

Gasification is a very versatile process and is used to convert a variety of hydrocarbon feedstocks, such as coal, lignite, oil distillates, residues and natural gas, into synthesis gas (“syngas”). IGCC systems use a combined cycle format with a gas turbine driven by the combusted syngas, while the exhaust gases are heat exchanged with water/steam to generate superheated steam to drive a steam turbine. Using an IGCC system, most of the power comes from the gas turbine (Chuah and Mohd Halim, 2010).

The syngas is produced at temperatures of up to 1700°C (in entrained flow gasifiers), whilst the gas clean up operates at a maximum temperature of 600°C. Large heat exchangers are required and there is the possibility of solids deposition in these exchangers which reduces heat transfer efficiency. It seems that unless it is possible to develop hot gas cleaning as a reliable procedure, the comparative economics of IGCC will remain unattractive. Figure 1.10 shows an example of a Taxaco IGCC plant.

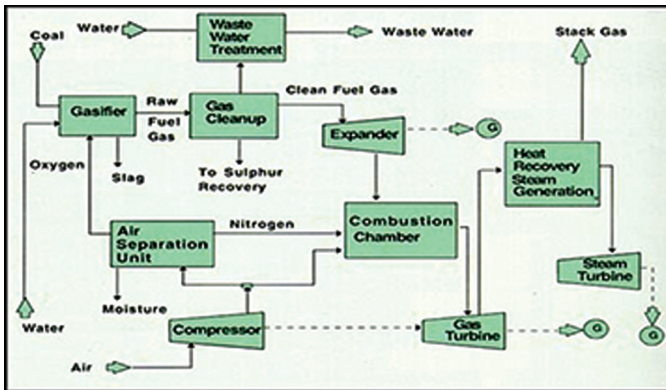


Figure 10 A Texaco IGCC power plant (Chuah, 2000) Air Blown Gasification Cycles

The use of coal-fired pressurised fluidised bed systems for power generation in the UK has been carried out at the PBFC facility. This culminated in the British Coal PFBC Topping Cycle concept (CFBC) system achieving better efficiencies and cost effectiveness together with a number of significant advantages compared with PBFC systems. Following this analysis, it was decided to develop the CFBC version of the Topping Cycle further which then became known as the Air Blown Gasification Cycle (ABGC).

In the ABGC, emission of particulates was monitored carefully during the development of the gasifier and CFBC components. In anticipation of more stringent emission legislation, specific components for gaseous and particulate species are now under development to improve the environmental performance of the ABGC.

Currently, emissions from the ABGC meet all current European and UK legislation without the need for additional gas cleaning. Incorporation of hot gas clean-up should enable the ABGC to meet the proposed, more stringent, requirements of the new European Large Combustion Installations Directive. Particulate emissions are controlled by the use of cyclones and filters. The hot fuel gas from the gasifier initially passes through a cyclone removing about 90 % of the entrained solids. The gas is then cooled to between 400-600oC before passing through the rigid ceramic filters. The filters act as a barrier filter, reducing dust loading to below 3 ppm by weight. This level of cleaning is required primarily to protect the gas turbine.

The British Topping Cycle developed by British Coal is an air blown gasification cycle (ABGC) which theoretically has a lower capital cost as it does not require an oxygen separation plant. The position of the ceramic filter between the gasifier and the gas turbine can be seen in Figure 1.11, a schematic of the British Topping Cycle and its major components. Typically, these installations have from more than 1000 candles to several thousands, e.g. 2072 filter candles have been used in the ELCOGAS power plant at Puertollano, Spain.

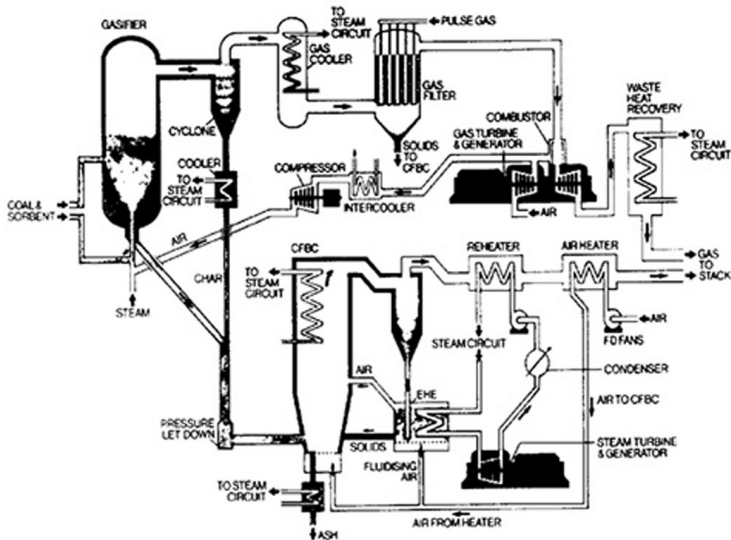


Figure 11 British Coal Topping Cycle (Chuah and Mohd Halim, 2010)

PULVERISED COAL-FIRED BOILER

A pulverised coal-fired boiler (PCFB) is the most commonly used method in coal-fired power plants, and is based on many decades of experience. Units operate at close to atmospheric pressure, simplifying the passage of materials through the plant.

The principal developments involve:

- increasing plant thermal efficiencies by raising the steam pressure and temperature used at the boiler outlet/steam turbine inlet;
- ensuring that flue gas cleaning units can meet emissions limits and environmental requirements.

Most pulverised coal-fired boilers operate with what is called a dry bottom. Combustion temperatures (with bituminous coal) are held at 1500-1700°C while with lower rank coals the range is 1300-1600°C. Most of the ash passes out with the flue gases as

fine solid particles, to be collected in electrostatic precipitators or filters before the stack.

CURRENT RESEARCH ON RIGID CERAMIC FILTERS FOR HOT GAS CLEANING

Currently, there are several research issues being investigated, summarised in Figure 12. In these investigations it is important to have a good understanding of the filtration process and particularly the cake detachment. Both issues depend very much on the fluid mechanics of the gas flow and the particle mechanics of cake formation and cake detachment. Table 6 summarises the major research issues related to the fluid mechanics and particle mechanics of filter operations. It is not always easy to reproduce the operating environment of a filter experiment and thus several techniques have been applied in order to predict the conditioning behaviour of the filter candle and to obtain better understanding of the filter operations (Seville et al., 2000).

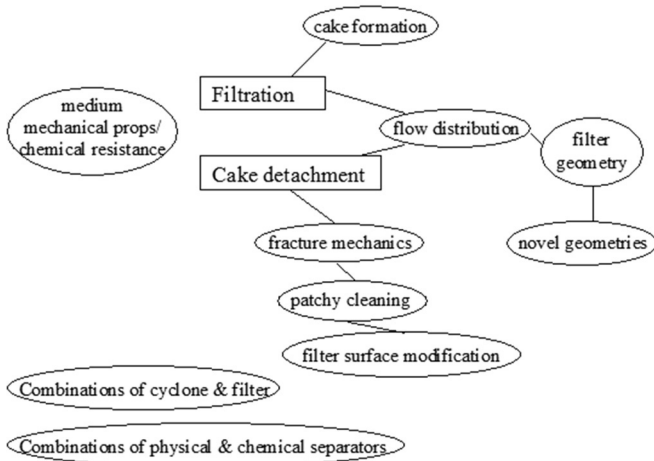


Figure 12 Research issues in the development of ceramic filters or hot gases

Filtration is the separation of a fluid-solids mixture involving passage of most of the fluid through a porous barrier which retains most of the solid particles. There are two major types of filtration behaviour: 'depth' filtration and 'surface' filtration. Two main phenomena, the filter cake build-up and cake removal, or specifically "conditioning", are important to optimise the filter operation and filtration efficiency. The main obstacles in achieving this are the operation variables and the dust and filter properties that are necessarily important, yet whose individual effects are not fully understood, such as the face velocity, areal loading of dust, temperature, pulse gas pressure, filter media resistance and dust properties. Particle diameter is also an important property that influences the cake formation. Further, operational variables such as reservoir or pulse jet pressure, temperature and face velocity all contribute to the filtration and filter cleaning operations. Incomplete cake removal or patchy cleaning also needs further investigation as it is still unclear where the transition to complete cake removal occurs.

The major research interests in this work are the study of the filter geometry, operation parameters to the flow field distribution on filtration and reverse flow cleaning and the investigation of cake formation and detachment by numerical study. This chapter covers review of some fundamental principles of filtration and reverse cleaning. The simulation details and discussion on filtration, reverse flow cleaning and cake detachment study on ceramic filters will be described in Chapters 3 - 5. The details of the mathematical models will also be described in those chapters. The results will be compared with the experimental data reported in previous works.

Table 6 The fluid mechanics and particle mechanics in filter operations

	Fluid Mechanics	Particle Mechanics
Filtration	Flow field distribution	Cake formation
Cleaning	Pulse propagation	Cake detachment

FILTRATION AND REVERSE PULSE CLEANING OF CERAMIC FILTER CANDLES

Filtration Theory

Filtration is the removal of solid particles from a continuous fluid phase (which in the current context is a gas) by passing the mixture through a porous filtering medium, on which the solids are deposited. Filter media include surfaces such as fibres, permeable solids and beds of small particles. A distinction can be drawn between the two main types of filtration behaviour: ‘depth’ filtration and ‘surface’ or ‘barrier’ filtration (Chuah et al, 2003). These are illustrated in Figure 13.

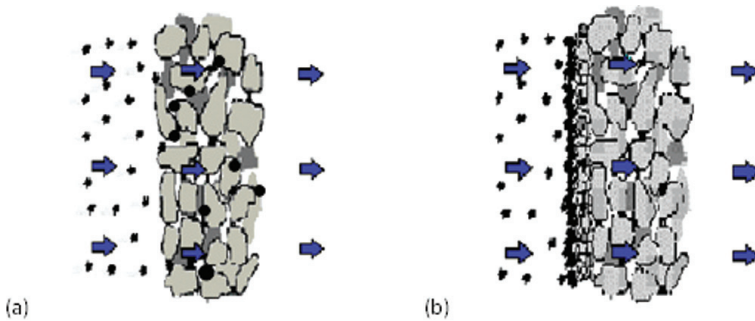


Figure 13 Filtration behaviour: a) ‘depth’ filtration and
(b) ‘surface’ filtration

In depth filtration, the collection of particles from the gas occurs throughout the filter medium. In surface filtration the medium acts as a barrier to the particles so that a filter cake is built up on the surface of the medium, with no penetration into the medium itself. In practice, the filtration behaviour depends on the properties of both the dust and the medium. The behaviour depends on the pore size of the filter and also the surface properties (such as adhesion) of both the dust and the filter medium. Perfect surface filtration is rare and with a new (“virgin”) surface filter, whereby penetration usually occurs for a short period of time before the cake is built up. During this time period, the filtration efficiency could be slightly lower than that in steady state operations.

A further important practical difference between depth filtration and surface filtration is that in general it is not possible to remove particles effectively from a depth filter after they have been captured. Surface or barrier filters are usually cleaned in situ, sometimes by shaking or other mechanical actions, but more commonly by administering a short pulse of pressurised gas in the opposite direction to that of the filtration flow. This detaches the cake into relatively large pieces, which then drop into a collection vessel for disposal or for recycling. Since this investigation is of a rigid ceramic filter which functions as surface filter, the discussion will be limited to surface filtration of particle laden gas.

Figure 14 illustrates the three phases of filter operations: (a) shows a virgin filter; (b) a filter cake is collected and forms on the surface of filter; and (c) a reverse pulse of cleaning gas is introduced directly into the throat of the filter candle. Entrained gas from the clean side temporarily changes its flow direction and is forced back out through the filter wall. This causes the filter cake to detach from the filter wall, and fall into the collection hopper at the bottom of the filtration vessel.

BASIC FACTORS IN FILTRATION OPERATIONS

There are four basic factors that are important in filter operations and testing. They are commonly used, either alone or in combination, to qualitatively analyze the operation of a filter. The first two are relatively easy to measure, whilst the third is very difficult to obtain outside bench-scale testing.

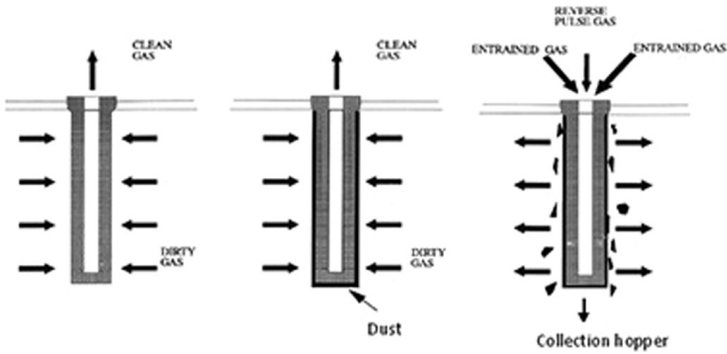


Figure 14 Three stages of filtration: (a) Virgin filter element; (b) filter cake built-up; and (c) cake detachment and removal (Chuah et al., 2003).

FACE VELOCITY

Mean face velocity, perhaps the most important variable in any filtration process, is defined as the surface normal flow rate through the filter medium. The face velocity, v_f , is defined mathematically as the actual volumetric flow rate, Q , divided by the total filtration area per candle, AC , and number of candles, n_c :

$$v_f = \frac{Q}{n_c A_c} \quad (2.1)$$

A typical value for rigid ceramic filtration is around 0.03 ms^{-1} , although velocities as high as 0.10 ms^{-1} have been used in some test applications. This is comparable to that of between 0.005 ms^{-1}

and 0.062 ms^{-1} for fabric filters. Note that this is not the same as the actual gas velocity within the filter, v_s .

PRESSURE DROP

The pressure drop, ΔP , is the primary dependent variable of the system. Much can be inferred about the performance of a filter by monitoring the pressure drop alone over a period of time. However, in a full-scale industrial application the conditions are rarely constant, so variations in the value of the pressure drop are often observed over short periods, although there is often no long term changes. One of the problems with observing the pressure drop is that it is susceptible to changes in temperature. The viscosity of a gas increases with increasing temperature, so that as the temperature in a filter increases, so does the pressure drop for a fixed flow-rate. This is accounted for by using a derived variable, k_1 , the filter resistance. Acceptable operational values of ΔP are from 1 kPa up to around 3kPa, depending on the application, flow-rates and temperature.

AREAL LOADING

Mean areal cake loading, w_A , defines the mass of dust present on the filter per unit filtration area. It is often used to quantify the capacity of a filter:

$$w_A = \frac{M}{n_c A_c} \quad (2.2)$$

where M is the total mass retained in the system, n_c is the number of candles in the system and A_c is the surface area available for filtration per candle. Areal loading is the maximum prior to reverse cleaning; where this maximum can be as high as several kg m^{-2} or as little as 100 g m^{-2} . The cake is often not fully removed and a

mass of the filtered dust may remain on the surface of the filter. This remaining mass is still thought of as part of the filter cake so the A_c value remains precisely constant. A_c is still defined as the surface of the filter, not the remaining dust layer accumulated on the filter surface. A phenomenon known as patchy cleaning occurs where the cake is not completely removed from the surface of the filter, leaving a patch like pattern. The patchy cleaning affects both the residual pressure drop and cleaning efficiency. In accordance with the cleaning strategies discussed above, research work is often done at fixed areal cake loading, whilst the majority of industrial applications rarely see a constant loading.

RESERVOIR PRESSURE

Reservoir pressure, P_R , is the pressure at which the cleaning pulse is supplied. The gas used for cleaning is stored in a pressure vessel which is sized to supply the full volume of cleaning gas required at the necessary pressure. Typically, for applications of the standard 1 metre length candle filter, the compressed air requirement per element is approximately 0.007 m^3 at STP. The actual volumetric flow rate entering the filter cavity, however, can be several times higher than the pressurised flow from the reservoir. This is due to the entrainment of gas from the surrounding atmosphere, as shown in Figure 15.

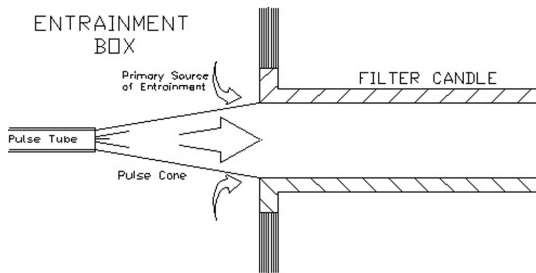


Figure 15 Gas entrains from the surrounding of the filter

When the gas is pulsed from the pulse tube, the free jet gas will entrain some of the surrounding gas and expand.

PARTICLE DEPOSITION IN SURFACE FILTRATION

The principal mode of operation for ceramic filter candles is surface filtration, i.e. the collected particles are retained on the surface of the filter and none penetrate into the structure. This is shown schematically in Figure 16. During the early stages of filtration, particles penetrate into the filter structure until “bridges” are formed across the pores, on which filtration continues to take place. A filter cake is then formed on the up-stream face of the surface and the penetration decreases. The pressure drop will increase approximately exponentially with time. Figure 17 shows a schematic of the penetration of the particles into the medium during the early stages of filtration.

During the first period of depth filtration, particles are collected by the principal mechanical capture mechanisms, namely:

- Inertial impaction;
- Direct interception;
- Diffusion; and
- Gravity

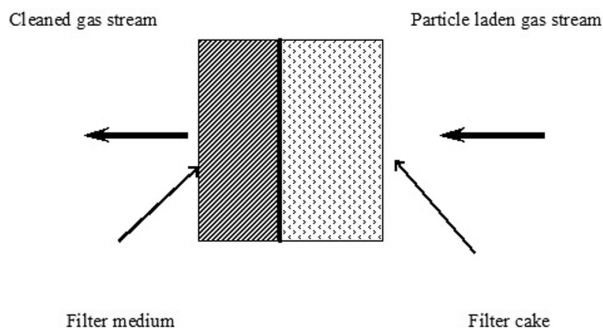


Figure 16 Perfect surface filtration

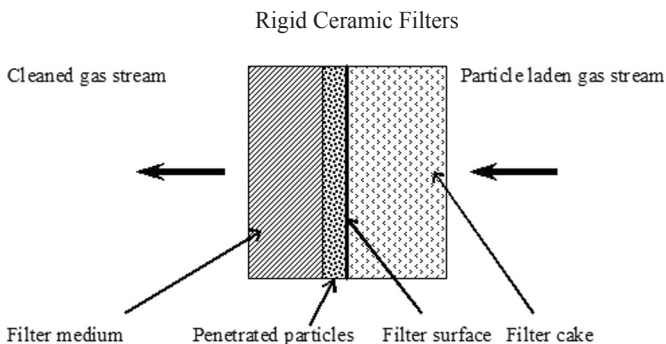


Figure 17 Particle penetration in surface filtration

MALDISTRIBUTION OF FLOW WITHIN A FILTER CANDLE

During filtration using rigid ceramic filters, the pressure drop across the filter wall is relatively low so that it can become comparable with the pressure drop axially along the clean gas side of the filter. Figure 18 shows the flow maldistribution in a filter during filtration operations.

The pressure drop across the wall is related to the resistance to flow of the filter medium.

This can be calculated using Darcy's Law for flow through a porous medium (in the appropriate form for a thick wall cylinder):

$$\Delta P = K\mu U \left[\ln \left(\frac{D_o}{D_i} \right) \left(\frac{D_o}{2} \right) \right] \quad (2.3)$$

where ΔP is pressure drop, D_i and D_o are internal and external filter diameters respectively, K is resistance to flow of the medium, U is the filtration face velocity and μ is gas viscosity.

CAKE FORMATION AND FILTER CONDITIONING

Aerosols will be collected on the surface of the filter if the pores available for gas flow through the filter are smaller than the particle

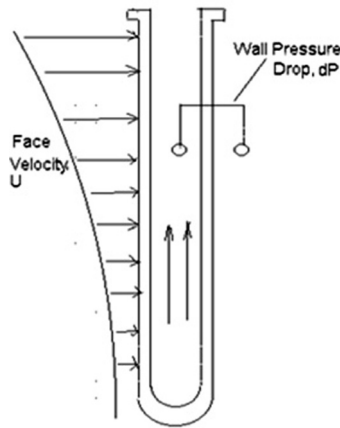


Figure 18 Flow maldistribution in a filter candle during filtration (Chuah, 2000)

size. Particles will be able to bridge the surface pores during the initial filtration period, even if the pore sizes are bigger than the diameter of the particles, and subsequent particle capture will happen in the post-deposited structure. An agglomeration of particles will build up a dust cake. Figure 19 shows the filter cake formation on the filter medium.

In general, barrier filters are operated cyclically. During filtration, dust builds up in the filter. After a prescribed time, or when the resistance to flow reaches a prescribed level, the medium is cleaned. The usual cleaning action is a reverse pulse of gas, applied to the clean side of the filter while it is online. This detaches the cake of deposit particles, which then falls into a collection hopper at the base of the unit, and subsequently the cycle is restarted. At the start of the next cycle, the pressure drop over the medium will be higher than the pressure drop for the virgin filter material. This increase in pressure drop is due to the presence of a residual dust layer and/or particles which have penetrated the filter medium and have not been removed by the cleaning action.

The “residual” pressure drop may continue to increase over many cycles. The time taken to reach a stable value is known as the “conditioning” period of the filter. Figure 20 shows the behaviour of two hypothetical media over many cycles of the filtration and cleaning schematically. The diagram shows “satisfactory” and “unsatisfactory” rise in the residual pressure drop for two filter media. The satisfactory performance of the first medium is defined by a short conditioning period, i.e. the rise of the residual pressure drop to a stable value takes place over a small number of cycles. In practice, the rise of the residual pressure drop to a stable value may take place over many hundreds of cycles. The second medium shows unsatisfactory behaviour since the residual pressure drop continues to rise over many filtration and cleaning cycles and may fail to reach a steady equilibrium value.

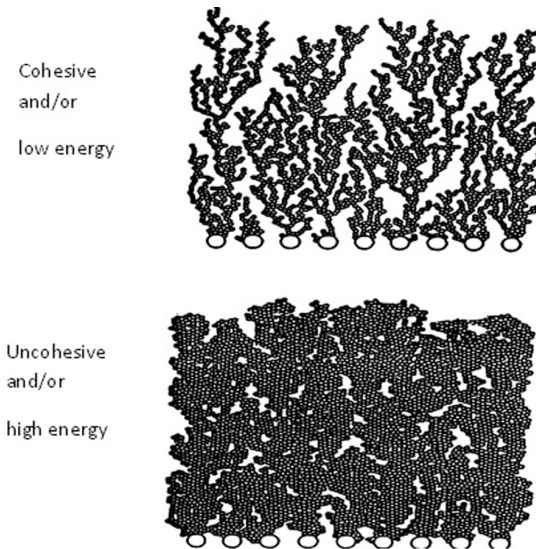


Figure 19 Cake formation: (a) Cohesive and /low energy particles build up a dendritic structure of high void fraction; and (b) uncohesive and/or high-energy particles form a dense cake. The larger circles represent the filter medium (Seville et al., 2000)

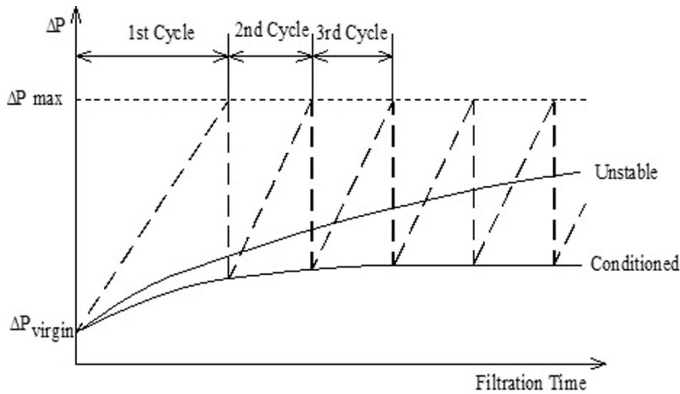


Figure 20 Schematic diagram of filter conditioning
(Stephen et al., 1996)

FILTRATION BEHAVIOUR OF DIFFERENT DUSTS

The filtration behaviour depends not only on the experimental conditions, but also on the characteristics of the powder. Grannell (1998) studied the influence of powder properties on the filter cake structure. Four different dusts were used in his studies, limestone, anatase TiO_2 , rutile TiO_2 and glass ballotini, which were filtered at a fixed velocity of 0.048 m s^{-1} . Figure 21 shows the cake pressure loss against the cake areal loading for the different dusts from Grannell's study. These findings show the strong influence of the particle size on pressure drop. Small particles tend to form denser cake structures and possess higher cake resistance. Hence the pressure across the cake is higher. For anatase TiO_2 , the particles agglomerate very easily and therefore have a larger 'particle' diameter than the original particle diameter. Thus, they are not able to penetrate into the filter medium.

Rigid Ceramic Filters

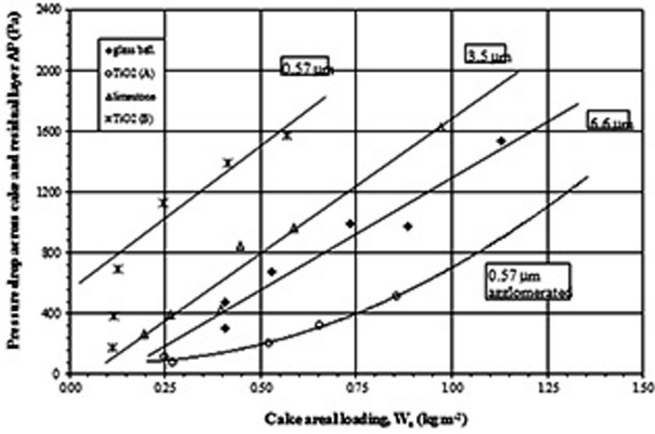


Figure 21 Cake and embedded particles pressure drop over cake areal loading for $v_f = 0.048 \text{ m s}^{-1}$ (Stephen et al., 1996)

RESISTANCE TO FLOW

In general, the pressure drop through a planar porous medium can be represented by the Ergun equation as:

$$-\frac{dP}{dl} = \frac{150(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu U}{d_p^2} + 1.75 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho U^2}{d_p} \quad (2.4)$$

which can be simplified as:

$$-\frac{dP}{dz} = k_1 \mu U + k_2 \rho U^2 \quad (2.5)$$

where

$$k_1 = \frac{150(1-\varepsilon)^2}{\varepsilon^3 d_p^2}$$

$$k_2 = 1.75 \frac{(1-\varepsilon)}{\varepsilon^3 d_p}$$

where $(-dP/dz)$ is the pressure gradient in the direction of flow; μ and ρ are the viscosity and density of the fluid respectively; ε is the void fraction, d_p is the particle diameter and U is the superficial fluid velocity, *i.e.* the actual volumetric flow rate divided by the area available for flow. In the case of the media considered here, as with fibrous media (Cheung et al., 1988), the fibre Reynolds number $(U\rho l/\mu)$ is much less than unity, where l is the filter wall thickness, so the viscosity term in Equation (2.5) will be dominant. The density term can thus be neglected and the equation be rewritten as Equation (2.6). k_1 can be replaced by the Carman-Kozeny expression as shown in Equation (2.7):

$$-\frac{dP}{dz} = k_1 \mu U \quad (2.6)$$

$$k_1 = K_K \frac{(1-\varepsilon)^2}{\varepsilon^3} S_o^2 \quad (2.7)$$

where S_o is the specific surface area of the medium and K_K is the Kozeny parameter, which depends on the geometrical structure. The Kozeny constant normally takes the value of 5 in fixed or slowly moving beds and granular materials up to porosity of 80% (Hesketh, 1986) and 3.36 in settling or rapidly moving beds.

MECHANISMS OF FILTER CLEANING

Effective cleaning is essential if the conditioning behaviour of the filter is to be acceptable and so it is clearly important to be able to assess the magnitude of the required cleaning action.

In a conventional fabric filter, it is usually assumed that the required tensile cleaning stress is set up primarily by the movement caused by the cleaning pulse. Pulse cleaning displaces the fabric outwards. When it becomes taut, it decelerates sharply, normally at many times the gravitational acceleration. The cake then

experiences tensile stress, which depends on its areal density and on the deceleration. If the stress is sufficient, the cake is thrown clear of the medium. Rigid filter media, such as ceramic filters, show no displacement on cleaning. The tensile stress is, therefore, entirely the result of the pressure drop imposed across the cake as a result of the reverse flow of the cleaning gas.

After a certain period of filtration, a uniform cake will have formed on the surface of the filter medium. A cleaning flow is then set up in the opposite direction to the filtration direction. During reverse-flow cleaning, a pressure difference (ΔP_T) will be set up across the filter, consisting of contributions from the cake (ΔP_c) and the medium (ΔP_m):

$$\Delta P_T = \Delta P_c + \Delta P_m \quad (2.8)$$

The gas viscosity is effectively constant and the cake and the medium thickness can be incorporated into modified resistances, k_c and k_m respectively so that:

$$\Delta P_m = k_m U \quad (2.9)$$

$$\text{and} \quad \Delta P_c = k_c U \quad (2.10)$$

Combining Equations (2.8) to (2.10), we obtained:

$$\Delta P_c = \Delta P_T \left[\frac{k_c}{k_c + k_m} \right] \quad (2.11)$$

where P_c denotes the pressure drop across the cake itself and also, as shown in Figure 2.10, tensile stress acting at the cake-medium interface.

THE RESIDUAL LAYER

Conventionally, the filter medium and filter cakes are thought of as separate entities. However, there is a “fuzzy” boundary between the filter medium and the filter cake. This boundary represents

the penetration of particles that enter into the depth of the filter medium which help trap other particles. The residual layer is responsible for a significant pressure drop, ΔP_R , which is dynamic during conditioning, but ultimately reaches a steady state value. The particles responsible for the conditioning pass a small way into the depth of the filter medium and are permanently trapped. They cannot be completely released or removed and only with vigorous mechanical cleaning can the pressure drop of a filter be returned to close to its virgin value.

REVERSE CLEANING AND CAKE REMOVAL

The assumption about cake removal inherent in the discussion thus far is that detachment occurs when tensile stress generated by the cleaning action overcomes either the adhesion of the cake to the filter medium or (more likely) the cohesive bond between particles (Figure 22). Therefore, when the required stress is achieved, simultaneous and complete removal should theoretically occur.

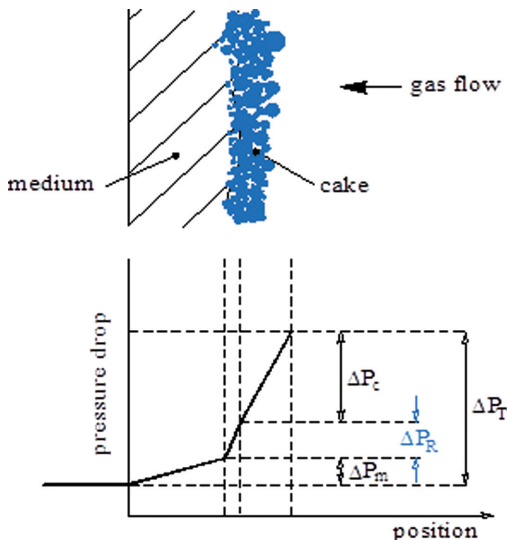


Figure 22 Residual layer and pressure drop components (Chuah, 2000)

In practice, however, cake removal is a progressive process. A schematic cake removal curve is depicted in Figure 23. It shows that the greater the cleaning stress, the more complete the removal of the cake from the filter surface, but in practice complete cake removal never occurs due to retention of the residual layer.

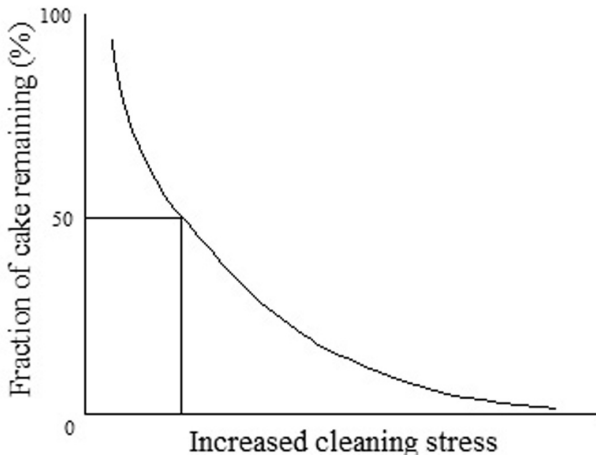


Figure 23 Schematic cake removal curve (Chuah, 2000)

The form of the cake removal curve is thought to be due to all cohesive bonds not being equal in strength and fractures originating at slight imperfections in the filter cake and flaws caused by irregularities on the filter surface. A distribution of particle sizes can lead to irregular packing of the dust which can also aid this effect.

PATCHY CLEANING

Patchy cleaning is an unusual effect which has been seen to occur in industrial and laboratory scale filtration. This phenomenon is depicted in Figure 24 where instead of the cake being removed in layers, incomplete cake removal occurs by removal of patches.

This occurs because during cleaning the applied tensile stress is greatest at the boundary between the filter cake and residual layer. Hence patches of filter cake that are completely removed in some parts of the filter come away from the residual layer boundary, leaving other areas completely intact.

It is clear that patchy cleaning can be overcome by having a thicker cake, i.e. increasing the areal cake loading, and/or increasing the pressure at which the filter is cleaned. There is a linear dependence of patch size on areal loading for specific dusts. It is likely that the exact relationship of these properties is dust-specific, and theoretically this relationship continues until, at a suitably high value of areal loading, the patches merge and complete cleaning occurs.

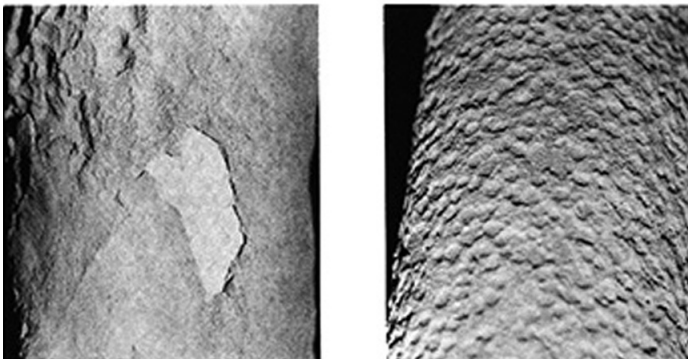


Figure 24 Patchy cleaning of fly ash from a granular silicon carbide candle filter at high temperature. Isolated patch shown on left and ‘orange peel’ effect due to repeated patchy cleaning shown on the right (Chuah et al., 2003)

Similarly, applying a larger cleaning stress would break a larger number of bonds in the filter cake with the same end result. The implication then is that patchy cleaning is indeed a fundamental behaviour of cake removal, but is often unobserved as the cake is usually completely removed.

COMPUTATIONAL FLUID DYNAMICS (CFD) MODEL ON CERAMIC FILTERS

INTRODUCTION

Earlier ceramic filter modeling was done using specific purpose code like PARTICULATE of Ahmadi and Smith (1999) and many other FORTRAN or MS Excel based code like in the one-dimensional model of Chuah et al. (1999b; 2004a; 2004b). They employed one-dimensional models and two-dimensional CFD simulations to model the candle filter and managed to obtain a reasonable prediction of pressure drop distribution, but no comparison was made on the velocity profile along the filter length.

THEORY

The cornerstones of computational fluid dynamics are the fundamentals governing equations of fluid dynamics - the continuity, momentum and energy equations. These equations are the mathematical statements of three fundamental physical principles upon which all of fluid dynamics is based:

1. Mass is conserved;
2. $F = ma$ (Newton's Second Law); and
3. Energy is conserved

In this present study, the energy balance is not involved, i.e. we have assumed that the gas is incompressible. Thus the equation for energy conservation is not developed.

THE CONTINUITY EQUATION

First, consider the model of a moving fluid element. The mass of the element is fixed and is given by dm . The volume (Figure 3.1) of this element is assumed as dV . Then

$$dm = \rho dV \quad (3.1)$$

where

$$dV = dx_1 dx_2 dx_3 \quad (3.2)$$

Since mass is conserved, the time-rate-of-change of the mass of the fluid element is zero as the element moves along with the flow. This means that:

Net mass flow out of control volume = time rate of decrease of
mass inside control volume

The mathematical expression of this statement can be represented in the form of a differential equation:

$$\iiint_V \left[\frac{\partial \rho}{\partial t} + \nabla \cdot (\underline{u}) \right] dV = 0 \quad (3.3)$$

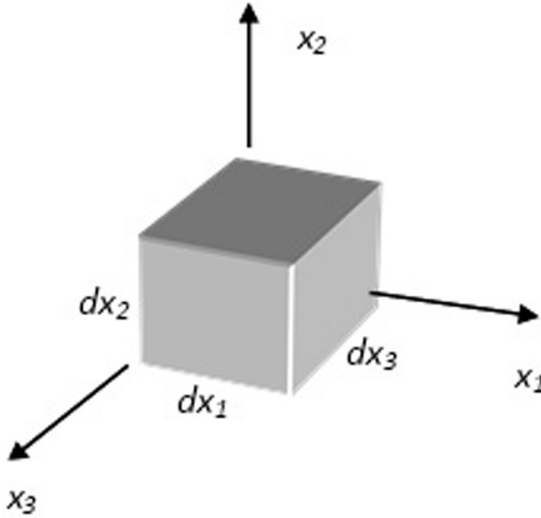


Figure 25 Volume element for derivation of the continuity equations

This is an application of the so-called Reynolds' transport theorem. Since the finite control volume is arbitrarily drawn in space, the only way for the integral in Equation (3.3) to equal to zero is for the integrand to be zero at every point within the control volume. Hence,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \underline{u}) = 0 \quad (3.4)$$

Equation (3.4) is called the continuity equation.

MOMENTUM EQUATION (NEWTON'S LAW)

The differential equation governing the conservation of momentum in a given direction for a Newtonian fluid can be written along similar lines, but the complication is greater because both shear and normal stress must be considered. The corresponding momentum equations can therefore be written as:

$$\rho \frac{D\underline{u}}{Dt} = \underline{F} - \nabla P + \nabla \cdot (\mu \nabla \underline{u}) + \nabla \cdot \underline{\underline{R}} + \underline{S} \quad (3.5)$$

where ρ is the density of the fluid, \underline{F} is a body force, P is hydrostatic pressure, $\underline{\underline{R}}$ is Reynolds stress or equivalent turbulent stress tensor, μ is dynamic viscosity and \underline{S} is a momentum source vector to account for porous boundaries. This is a generalised incompressible Navier-Stokes equation.

MESH GENERATION

The numerical solution of partial differential equations requires some discretisation of the field into a collection of points or elemental volumes (cells). The differential equations are approximated by a set of algebraic equations on this collection, and this system of algebraic equations is then solved to produce a set of discrete

values which approximate the solution of the partial differential system over the field. The discretisation of the field requires some organisation for the solution thereon to be efficient, i.e., it must be possible to readily identify the points or cells neighbouring the computation site. Furthermore, the discretisation must conform to the boundaries of the region in such a way that the boundary conditions can be accurately represented.

A numerically-generated grid is understood here to be the organised set of points formed by the intersections of the lines of a boundary-conforming curvilinear co-ordinate system. The use of co-ordinate line intersections to define the grid points provides an organisational structure which allows all computations to be done on a fixed square grid when the partial differential equations of interest have been transformed, so that the curvilinear co-ordinates replace the Cartesian co-ordinates as the independent variables. This grid frees the computational simulation from being restricted to certain boundary shapes and allows general codes to be written in which the boundary shape is specified simply by input. The boundaries may also be in motion, either as specified externally or in response to the developing physical solution. Similarly, the co-ordinate system may be adjusted to follow variations developing in the evolving physical solution.

In any case, the numerically generated grid allows all computations to be done on a fixed square grid in the computational field which is always rectangular in construction. In this case, finite volume methods are applied. The methods, as related to finite difference methods, are derived by volume integration of the equations of motion, with application of the divergence theorem and reducing the order of the differential equations by one. Equivalently, macroscopic balance equations are written on each cell.

GRID GENERATION AND NUMERICAL IMPLEMENTATION

FLUENT is a two part package consisting of a preprocessor and a main module, FLUENT. A CAD-style program is used for geometry set-up and grid generation in 2D or 3D. It is used to define the geometry and a structured grid for the model. As illustrated in Figure 3.2, the grid information is transferred from the preprocessor to FLUENT in a grid file. Following this transfer, FLUENT can be used to define physical models, fluid/material properties and boundary conditions. This information is added to the grid information and stored in a Case File that keeps a record of all inputs. The calculation is then performed in FLUENT, with the results of the calculation being stored in a Data File.

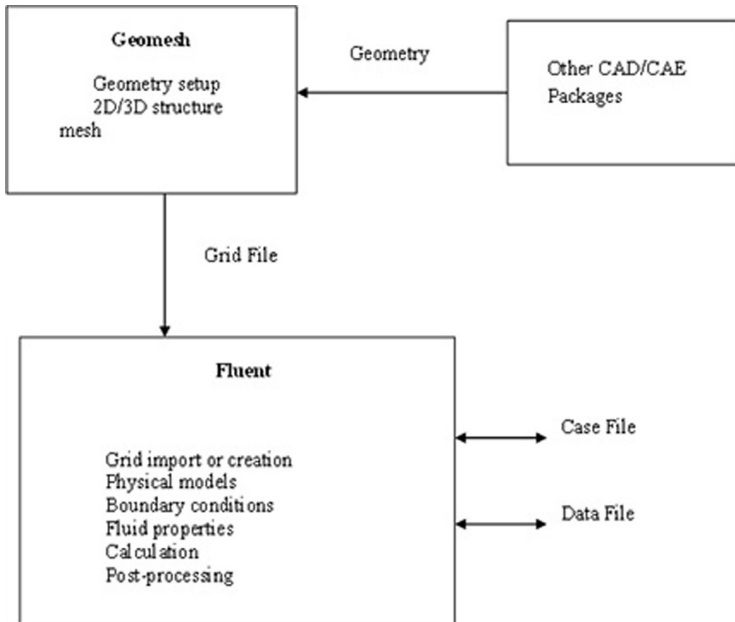


Figure 26 FLUENT basic program structure

BOUNDARY AND INITIAL CONDITIONS

Boundary conditions must be specified at the inlet, outlet and the walls. The ambient and wall temperatures are set to 298K. At the inlet, the feed stream pressure is defined and the cells at the open end of the filter are set as the pressure outlet. A 1.0 meter length porous section is employed in the filter wall which is permeable. The following Darcy equation can thus be used to describe the conditions on the surface:

$$\frac{\mu}{\alpha_{filter}} \underline{u} + \frac{\partial p}{\partial x} = 0 \quad (3.6)$$

where μ is the viscosity of the air (assumed to be constant) and α_{filter} is the porous wall permeability coefficient in both radial and axial directions, x is denoted as the filter thickness, \underline{u} is the velocity and p is the pressure. Equation (3.6) describes the flow of the air through the porous wall of the filter element. The equation can be further simplified as:

$$\Delta P = -x \frac{\mu}{\alpha_{filter}} \underline{u} \quad (3.7)$$

Meanwhile, the flow inside the filter can be described by the cylindrical co-ordinate Navier-Stokes equations with azimuthal symmetry as:

$$\rho \left(\frac{\partial u_z}{\partial t} + u_z \frac{\partial u_z}{\partial z} + u_r \frac{\partial u}{\partial r} \right) = \rho Z - \frac{\partial P}{\partial z} + \mu \left(\frac{\partial^2 u_z}{\partial z^2} + \frac{1}{r} \frac{\partial u_z}{\partial r} + \frac{\partial^2 u_z}{\partial r^2} \right) \quad (3.8)$$

$$\rho \left(\frac{\partial u_r}{\partial t} + u_z \frac{\partial u_r}{\partial z} + u_r \frac{\partial u_r}{\partial r} \right) = \rho R - \frac{\partial P}{\partial r} +$$

$$\mu \left(\frac{\partial^2 u_r}{\partial z^2} + \frac{1}{r} \frac{\partial u_r}{\partial r} - \frac{u_r^2}{r^2} + \frac{\partial^2 u_r}{\partial r^2} \right) \quad (3.9)$$

where r indicates the radial direction and z indicates the axial direction in the filter candle and Z and R indicate the z and r direction components of external forces acting on the fluid of unit mass respectively.

ASSUMPTIONS

In setting up the ceramic filter model the following assumptions were made (Chuah and Seville, 1999; Chuah et al., 1999):

1. The flow is axi-symmetric;
2. Fluid is incompressible and has constant properties; and
3. The solid phase is assumed to follow the field flow because the particulates are very small (typically with median size weight of less than 10 μm).

Since dust is assumed to have no influence on the flow, the governing equation for the gas flow can be described as an ordinary Navier-Stokes equation:

$$\frac{D(\rho \underline{u})}{Dt} = -\nabla P + \mu \nabla^2 \underline{u} \quad (3.10)$$

CFD SIMUALATION ON CERAMIC FILTERS

The internal flow dynamics and pressure drop in the filter element are determined via the solutions of the conservation equations. Mathematical modeling of the flow in a full sized three dimensional filter element was performed using CFD code, FLUENT 6.1. The internal flow dynamics and pressure drop in the filter element were determined via the solution of conservation equations. A finite volume technique was employed to ensure that all solutions satisfy the conservation equations and provide solution stability and accuracy. The candle ceramic filter was represented using a

full scale tetrahedral mesh that consisted of 1935 nodes as shown in Figure 27.

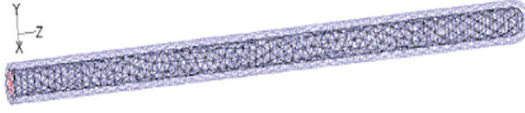


Figure 27 The CFD computational mesh on a ceramic filter

A velocity inlet boundary was used to specify the filter surface range from 4 to 6 cm/s while an outflow boundary condition was used to represent the filter's open end. The filter element was modeled via a porous media model available in FLUENT (Jolius Gimbut et al., 2009). The porous media was modeled by additional momentum source terms to the standard fluid flow equations. The source term is composed of two parts, a viscous loss term (Darcy) and an inertial loss term. The anisotropic vectorised Ergun equation is thus:

$$S_i = \sum_{j=1}^3 D_{ij} \mu u_j + \sum_{j=1}^3 c_{ij} \frac{1}{2} \rho |\underline{u}_j| \underline{u}_j \quad (3.11)$$

where S_i is the source term for the i th (x, y, z) momentum equation, and D and C are prescribed matrices. The momentum sink contributes to the pressure gradient in the porous cell, creating a pressure drop that is proportional to fluid viscosity and momentum in the cell. Assuming a simple isotropic, homogeneous porous media, Equation (3.11) can be rewritten as:

$$S_i = \frac{\mu}{\alpha} u_j C_2 \frac{1}{2} \rho |\underline{u}_i| \underline{u}_i \quad (3.12)$$

where α is the permeability and C_2 is the inertial resistance factor. In laminar flows through porous media the pressure drop is typically proportional to viscosity and the constant C_2 can be considered to

be zero. Ignoring convective acceleration and diffusion, the porous media model, then reduces to Darcy's Law:

$$\nabla P = -\frac{\mu}{\alpha} \underline{u} \quad (3.13)$$

The permeability value, $\alpha = 6.3 \times 10^{-12} \text{ m}^2/\text{s}$ is adopted from the experimental work of Chuah (2000). The finite volume methods were used to discretise the partial differential equations of the model for pressure-velocity coupling and the second order scheme to interpolate the variables on the surface of the control volume. The segregated solution algorithm was selected and the laminar model was also applied to the porous region.

CFD SIMULATION RESULTS AND DISCUSSION

Chuah (2000) performed a detailed measurement of pressure drop and velocity profile along the filter candle, varying the face velocity from 4 cm/s to 6 cm/s. Aware of the availability of Chuah's experimental data for validation, the CFD simulation was also performed using the same face velocity. Figure 28 shows the contour of the velocity magnitude along the center region of the filter candle.

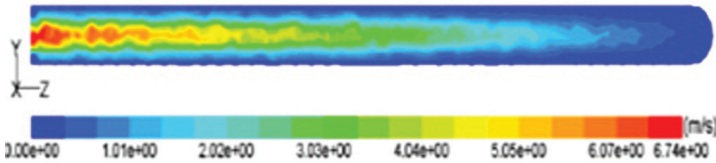


Figure 28 Contour map of velocity magnitude along the center region of the filter candle

The velocity magnitude in the hollow region of the filter shows an increasing trend as it was moving towards the open end where the pump is situated in the actual experiment. The highest velocity magnitude can be spotted in center region of the filter near the open end. This higher velocity created a lower local static pressure which inevitably lead to a higher pressure drop in this region. The contour of the static pressure along the center region of the filter candle in Figure 29 clearly shows evidence of a lower static pressure at the open end of the filter candle.

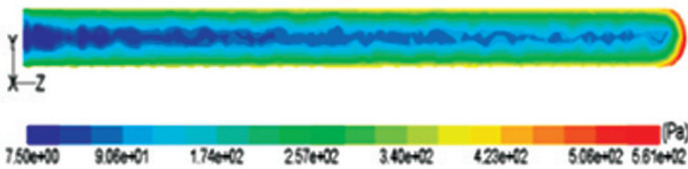


Figure 29 Contour map of static pressure at the center region of the filter candle

The pressure drop for the ceramic filter was calculated by obtaining the differences between static pressure at the filter's center axis and also static pressure at the surface of the filter model. Figures 30 to 32 show the calculated pressure drop at various mean surface velocities which were compared with experimental data from Chuah (2000). The CFD prediction is in good agreement with the experimental data of Chuah (2000) within about 5% average error, which might be in the same range of the experimental error. The assumption of an isotropic flow resistance for the porous zone modeling is suspected to have attributed to the error. It is safe to assume an isotropic media resistance in x and y directions where the internal velocity did not differ appreciably, but the same may not be true for the z direction. In this study, the media resistance acting in the z direction is calculated by taking into consideration

the average internal z velocity, hence, it represents the average value rather than the local ones. Consequently, this assumption lead to a slight over prediction of the pressure drop profile. Nevertheless, the effect of the media resistance in the z direction is minimal considering the fact that most of the gas flowing through the filter element (porous media) is in the x and y directions. For that reason, the CFD prediction is considered to be in close agreement with the experimental measurements, despite using the isotropic media resistance assumption.

The commonly observed phenomenon of pressure drop increasing proportionally with the advancing face velocities was also reproduced correctly by the CFD simulation. These increases are attributed by the fact that the media resistance in Darcy's law increases proportionally with the square of face velocity. It should also be noted that the pressure drop at the open end was slightly higher compared to the pressure drop at the closed end. These trends of an increasing pressure drop towards the open end of the filter candle are attributed by the increases in the velocity magnitude inside the hollow region of the filter. The rise in velocity magnitude towards the open end of the filter is attributed by the continuous flow of gas moving through the filter media along the filter candle. Comparison of the calculated and measured velocity profile along the candle enter region is shown in Figure 32. The CFD prediction shows fair agreement with the experimental data reported by Chuah (2000) and Chuah et al. (2004). The trend of higher velocity at the open end of the filter has also been successfully elucidated numerically. These increasing velocity trends, as mentioned earlier, are associated with the constant inflow of gas along the filter length.

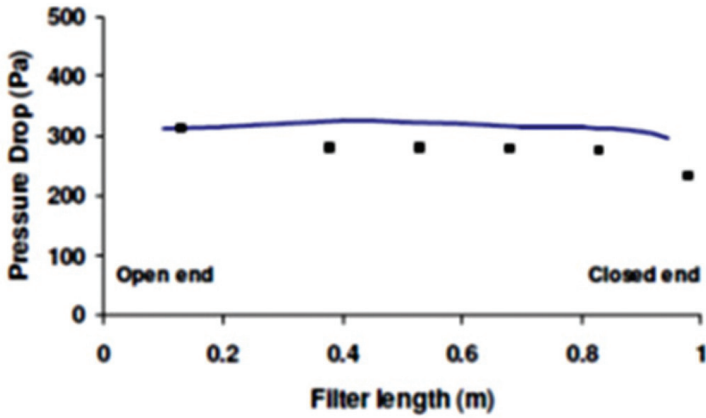


Figure 30 Prediction of pressure drop along the filter length at face velocity 4 cm/s. Data points are adapted from Chuah (2000) and Chuah et al. (2004)

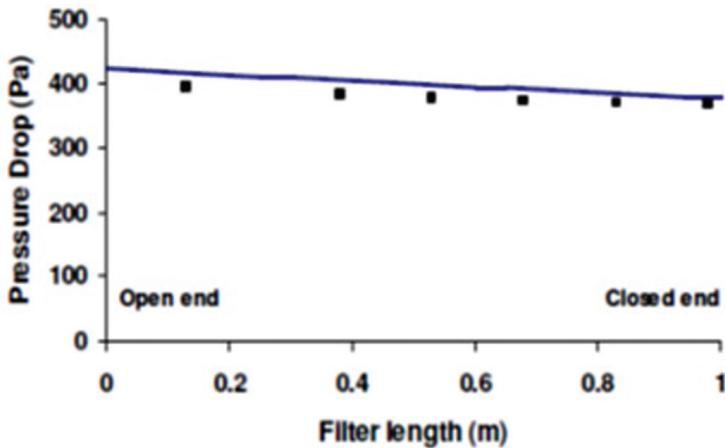


Figure 31 Prediction of pressure drop along the filter length at face velocity 5 cm/s. Data points are adapted from Chuah (2000) and Chuah et al. (2004)

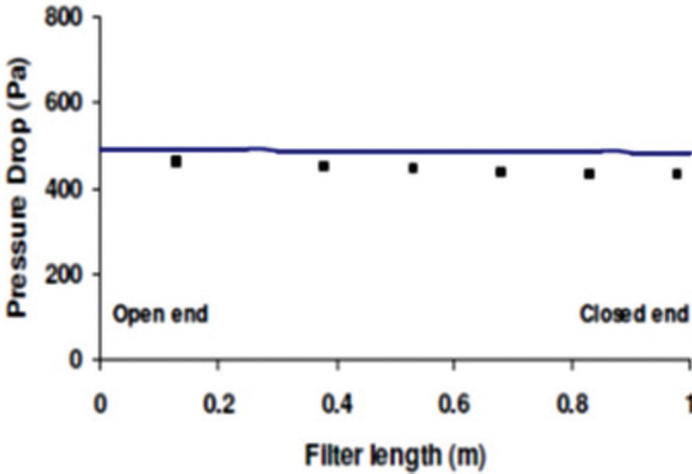


Figure 32 Prediction of pressure drop along the filter length at face velocity 6 cm/s. Data points are adapted from Chuah (2000) and Chuah et al. (2004)

REVERSE FLOW MODELLING USING EXCEL

INTRODUCTION

This section proposes a simple simulation method for predicting the flow field in the filter during the cleaning process. A computer program has been written to model the flow of the reverse pulse air, from the cleaning bar nozzle to the dirty side of the filter. The programme uses the iterative calculation mode of Microsoft Excel and allows variables such as pulse pressure and filter geometry to be changed (Chuah, 2000; Chuah et al., 2005).

The model can be used to investigate the effect of the operational parameters and filter properties, such as pulse tube distance, friction factor, pulse gas temperature, reverse pulse pressure and reverse flow rate, on the pressure difference over the candle wall and axial

velocity profile. It can also be used to predict the cleaning behaviour of the tapered filter element.

EFFECT OF PULSE TUBE DISTANCE

The aim of this work was to investigate the effect of the pulse tube position, relative to the open-end of the filter candle, on the pressure difference along the filter element. Using the Excel model, comparison with his data was carried out. Figure 33 shows the schematic diagram of the distance of the pulse tube position. x indicates the distance of a pulse jet tube from the open end of the filter.

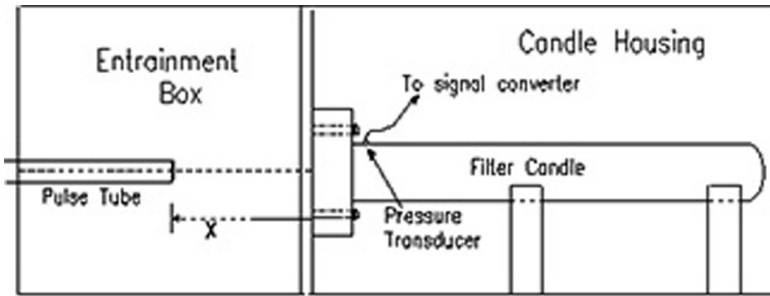


Figure 33 Schematic diagram showing measurement of pulse tube distance

Grannell (1998) found that 13.5cm from the open end was the optimum distance for a 40 mm candle opening as this was the distance at which no “secondary” entrainment of gas occurred through the filter wall (for 4 bar cleaning pulse pressure).

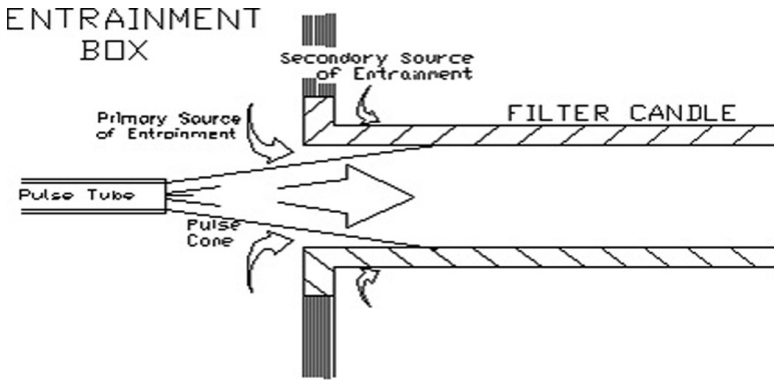


Figure 34 Pulse tube distance too short (Grannell, 1998)

Secondary entrainment is normally caused by the pulse tube being too close to the filter opening. As the gas is pulsed from the tube a large quantity of pulse gas extends into the filter. Secondary entrainment gas enters from the throat of the filter (Figure 34) in the opposite direction of the cleaning flow and will suck dusty gas through the round throat of the filter. After several cycles of conditioning, a dust cake will be retained around the open end of the filter and will be difficult to detach.

Figure 35 shows the comparison between the simulation data and the data obtained from Grannell's experiments. In his work, the range of pulse tube distance over which the secondary entrainment occurred was between 8 and 14 cm. Two pulse tube distances were used in this simulation, 12 and 13.5cm (optimum distance according to Grannell). The simulation result was in good agreement with the experimental data. Thus this model will henceforth be used to predict the effect of the tube distance on the pressure difference profile.

Figure 36 shows the effect of two different pulse tube distances, 8cm and 15cm, on the pressure difference profile. As the tube distance increased from 8cm to 12cm, the peak pressure at the closed end of the candle increased by 150%. For a pulse tube distance of 15cm, the peak pressure increased by about 180% compared with the pressure at a pulse tube distance of 8cm. This increment in pressure difference was due to the larger quantity of gas being forced into the filter flow at the greater tube distance. Larger axial velocities were converted into gas momentum and hence contributed to the pressure difference across the filter wall. However, as the distance increased, the rise in pressure difference became less significant.

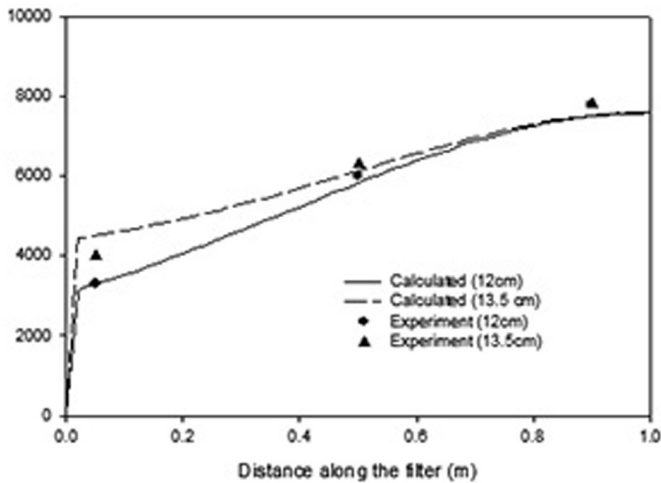


Figure 35 Comparison of the simulation and the experimental data with a pulse pressure of 4 bars

Rigid Ceramic Filters

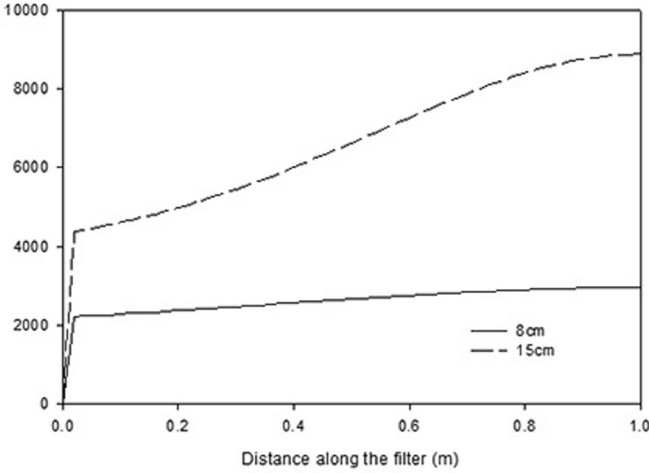


Figure 36 Effect of the pulse tube distance from the open end to the pressure difference with a pulse pressure of 4 bars

EFFECT OF FRICTION FACTOR

Figure 4.5 shows the variations in the local pressure difference across the filter wall, from the open end toward the closed end, using three different friction factors, 0.01, 0.05 and 0.1, respectively (corresponding to a surface roughness of 1mm, 6.5mm and 15mm, respectively, calculated by Colebrook-White equation). For the flow in the filter with a friction factor of 0.01, it can be seen that local pressure difference across the wall increases from the open end to the closed end. A different outcome was noticed when the internal wall friction was 0.05, whereby the local pressure difference across the wall decreased with increasing distance from the open end of the filter. Increasing friction factor will hence reduce the pressure drop as described in Equation (4.1):

$$\frac{dP}{dz} + \frac{1}{2} \frac{d}{dz} (\rho u_z^2) = -4 \frac{f}{D_i} \frac{1}{2} \rho u_z^2 \quad (4.1)$$

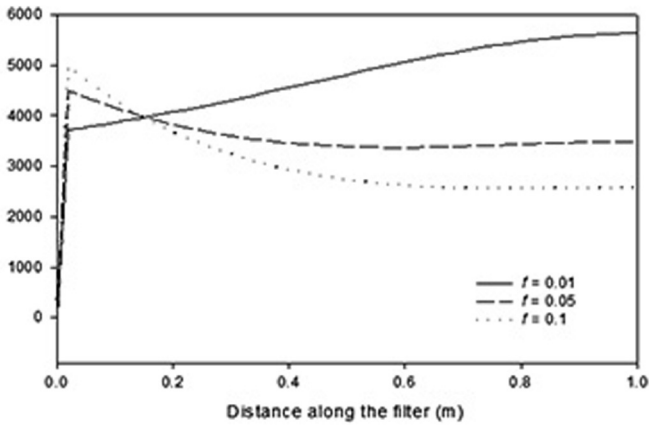


Figure 37 Effect of the friction factor on the pressure difference profile with a reverse pulse pressure of 4 bars

However, the profile of decrement in pressure difference was not continuous and it passed through a minimum before the closed end was reached.

The effect of the friction was also noticed when the friction factor was increased to 0.1. There was an initial decrease in the pressure difference across the wall at the open end and this reached a minimum at a distance of 70cm from the open end. There was a slight increment in the pressure difference across the filter wall close to the closed end.

Figure 38 shows the changes in volumetric flow rate along the filter candle for different friction factors. At the higher friction factor, there was greater volumetric flow rate decrease from the open end of the filter towards the closed end of the filter. As the gas flow travelled along the filter from the open end to the closed end of the filter, the axial velocity was recovered as static head, thus increasing the pressure difference across the wall. The volumetric flow rate decreased monotonically to reach zero at the closed end. For friction factors of 0.05 and 0.1, with a large volumetric flow rate

at the open end, the frictional effects were large and the pressure difference across the wall was decreased. However, at a distance of 60cm from the open end, the pressure drop caused by friction was reduced because the volumetric flow is then small and makes little contribution to the pressure difference across the wall. The loss of momentum of the gas flow then dominates the axial pressure drop and pressure recovery occurs. The frictional pressure drop scales with Q^2 , hence, as Q decreases, the contributions of the frictional terms are strongly reduced.

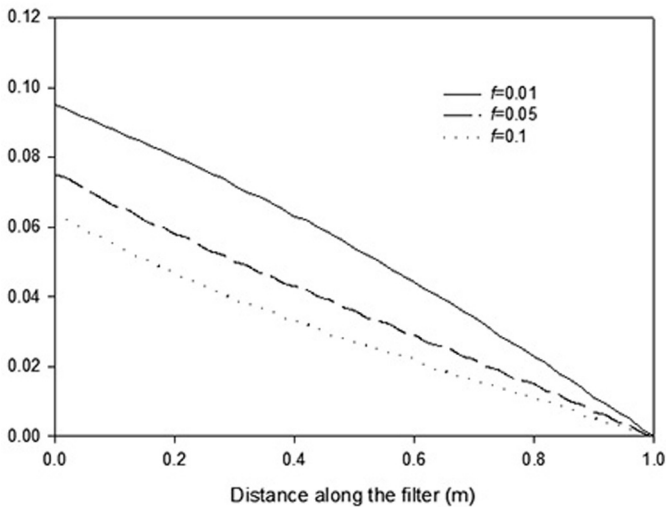


Figure 38 Effect of the friction factor on the pressure difference profile with a reverse pulse pressure of 4 bars

EFFECT OF TEMPERATURES

An important concern in filter cleaning is the progressive loss in filter strength with use. The thermal stress set up during pulse cleaning will weaken the ceramic substrate of the filters. For the cleaning process, a high temperature jet of gas is reverse passed

through the hot ceramic filter which should be at a temperature greater than ambient. This is to avoid the thermal stresses set up during pulse cleaning, which will weaken the ceramic substrate. Research at the University of Aachen (Schiffer et al., 1989) has confirmed that a severe temperature transient occurs during pulse cleaning when using ‘cold’ pulse gas. To reduce this problem, a venturi eductor was introduced.

Figure 39 shows the effect of the pulse jet gas temperature on the pressure difference profile along the filter element. When the temperature of the jet gas was increased, from 20°C to 200°C, the pressure difference increased by 23% at the open end and 15% at the closed end of the filter. However, at higher temperatures, 300°C and 400°C, the open end pressure differences were 32% and 38%, respectively, higher than at 20°C, with very little increment in the pressure difference at the closed end.

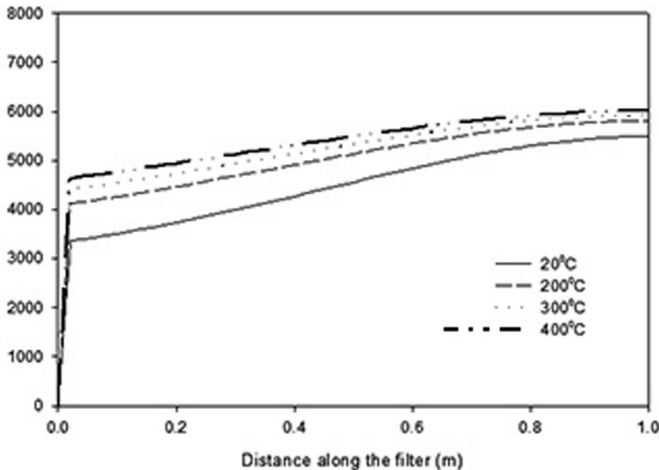


Figure 39 Effect of pulse jet temperatures on pressure difference profile

At 20oC, the local pressure increased with increasing distance from the open end of the filter candle, but the change in local pressure was reduced at higher temperatures and was not significant. At a temperature of 20oC, the pressure difference increased by 63% from the open end to the closed end, whilst at 300oC and 400oC the pressure difference at the closed end was only 35% and 30% higher from that at the open end, respectively.

Increasing temperature will increase the gas viscosity and hence will increase the pressure drop across the filter wall. At the same time, the gas density will decrease with increasing temperature and hence reduce the pressure changes along the filter candle, which are largely due to momentum effects (Chuah and Seville, 2002). The combination of these effects tends to reduce non-uniformity, as shown in Figure 39.

SIMULATION OF DUST CAKE BUILD-UP ON THE FILTER MEDIUM

INTRODUCTION

This section describes a physical model for cake and pressure build-up on candle filters. The model was aimed at investigating filtration operations and reverse pulse cleaning of the filter. It is useful to calculate the filter cake thickness and pressure drop along the filter candle. Figure 40 shows a schematic diagram of filter cake build-up on the filter surface.

MODEL AND ASSUMPTIONS

The model used here omits several factors that may affect the filtration operations and is therefore considerably “idealised”. This model is thus principally targeted to describe the most important

physics of filtration before its secondary effects are taken into consideration.

The model derivation makes the following assumptions (Chuah and Seville, 2004):

- i. All particles entering the filter housing are deposited on the surface of the filter.
- ii. The filter cake and the filter medium obey Darcy's law.
- iii. The gas is incompressible.
- iv. To simplify the model, the small area at the bottom of the filter (closed end, about 1% of the total filter surface), for which the gas flow rate differs significantly from the rest of the filter, is ignored in the subsequent analysis.

Filter 'conditioning' or 'blinding', i.e., the penetration of fine particles into the filter pores, may sometimes occur and increase the pressure drop across the filter.

FLOW THROUGH THICK FILTER

Seville et al. (1989) suggested a numerical expression to define the pressure drop through a thick-walled rigid filter. Consider a flow at face velocity, U_o , through a thick-walled cylindrical filter of outside diameter, D_o , and internal diameter, D_i . The volumetric gas inflow per unit length of the filter candle is thus $\pi D_o U_o$. Neglecting any changes in gas density as it passes through the porous medium, the superficial velocity at any intermediate radius r is thus:

$$U = U_o D_o / 2r \quad (5.1)$$

Assuming the radial flow is a viscous flow (i.e. Re is small), Darcy's law can be applied:

$$\frac{dP}{dr} = -k_1 \mu U = -\frac{k_1 \mu U_o D_o}{2r} \quad (5.2)$$

The total pressure drop across the filter candle wall is thus given by:

$$\Delta P_f = \int_{\frac{D_i}{2}}^{\frac{D_o}{2}} \frac{k_1 \mu U_o D_o}{2r} dr \quad (5.3a)$$

$$= \frac{k_1 \mu U_o D_o}{2} \int_{\frac{D_i}{2}}^{\frac{D_o}{2}} \frac{dr}{r}$$

$$= \frac{k_1 \mu U_o D_o}{2} \ln \left[\frac{D_o}{D_i} \right] \quad (5.3b)$$

Figure 5.2 shows a schematic diagram of the flow through a thick filter candle wall. The calculation is then extended into the filter cake build-up model.

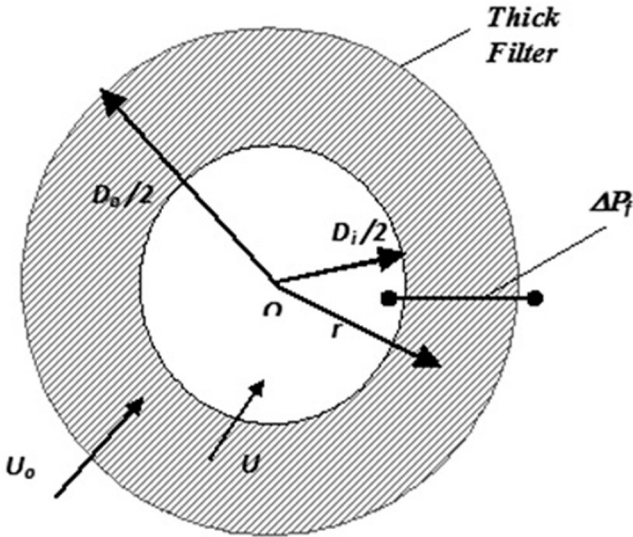


Figure 41 Schematic diagram of flow through thick filter candle

Due to the cylindrical geometry of the filter and filter cakes, Darcy 's law needs to be solved in polar coordinates. Neglecting any changes in gas density as it passes through the porous dust medium, the superficial velocity at any intermediate radius r_c as stated earlier is given by;

$$U_c = U_o \frac{D_o}{2r_c} = U_o \frac{D_o}{D_c} \quad (5.4)$$

Hence, the pressure drop across the filter cake between the filter medium and dust cake is:

$$\Delta P_c = \frac{k_2 \mu U_c D_c}{2} \ln \left[\frac{D_c}{D_o} \right] \quad (5.5)$$

where, k_2 is the cake resistance, D_c is the outer diameter of filter cake and U_c is the superficial velocity through the outer radius of cake (Figure 42).

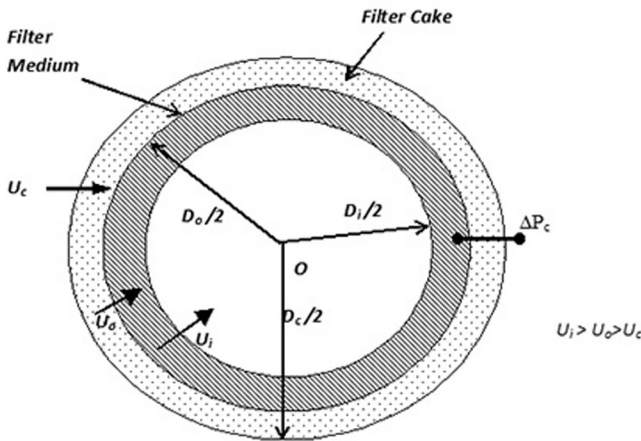


Figure 42 Schematic diagram of flow through a filter candle and filter cake

The constant gas flow rate into the filter vessel, Q (volumetric flow rate per unit length) can thus be written as:

$$Q = \pi D_c U_c = \pi D_o U_o = \pi D_i U_i \quad (5.6)$$

Then, U_c can be rewritten as:

$$U_c = \left(\frac{D_o}{D_c} \right) U_o \quad (5.7)$$

Further, the thickening rate of the cake formed on the surface of the filter can be determined by a dust volume balance:

$$\frac{dx}{dt} = \frac{w U_c}{\rho_c} \quad (5.8)$$

$$\Delta x = \int \frac{w U_c(t)}{\rho_c} dt \quad (5.9)$$

where w is the dust concentration (kg/m^3) in the gas flow, which has been taken to be constant, ρ_c is the cake density and Δt is the time interval from $t = 0$ to time t . Cake density is thus defined as:

$$\rho_c = \rho_p (1 - \varepsilon_c) \quad (5.10)$$

where ρ_p is the particle density and ε_c is filter cake porosity.

The outer diameter of the filter cake over Δt is then calculated as:

$$D_c(t) = D_o + \Delta x \quad (5.11)$$

The total pressure drop across the filter medium and dust cake is then derived as:

$$\Delta P_T = \Delta P_f + \Delta P_c \quad (5.12)$$

When $t = 0$, no cake is formed and the pressure difference is equal to the pressure difference across the clean filter.

$$\Delta P_T = \Delta P_f \quad (5.13)$$

When $t = t_1$, dust starts to accumulate on the filter surface, then

$$\Delta x_{t_1} = \int_{t_0}^{t_1} \frac{w U_c(t)}{\rho_c} dt \quad (5.14)$$

$$D_c(t) = D_o + \Delta x \quad (5.15)$$

$$D_{c,t_1} = D_o + \int_{t_0}^{t_1} \frac{w U_c(t)}{\rho_c} dt \quad (5.16)$$

The pressure difference between the filter medium and dust cake when $t = t_1$ is

$$D_{c,t_1} = D_o + \int_{t_0}^{t_1} \frac{w U_c(t)}{\rho_c} dt \quad (5.17)$$

and

$$U_c(t_1) = \left(\frac{D_o}{D_{c,t_1}} \right) U_o \quad (5.18)$$

Equation (7.17) is then rearranged as:

$$\Delta P_{c,t_n} = \frac{k_2 \mu U_o D_o}{2} \ln \left[1 + \frac{\Delta x_{t_1}}{D_o} \right] \quad (5.19)$$

As the dust accumulates, and the changes in face velocity do not affect the structure of the dust

cake, $t = t_n$:

$$D_{c,t_n} = D_o + \frac{w}{c} \left[\int_{t_0}^{t_1} U_c(t) dt + \int_{t_1}^{t_2} U_c(t) dt + \dots \int_{t_{n-1}}^{t_n} U_c(t) dt \right] \quad (5.20)$$

$$\Delta P_{c,t_n} = \frac{k_2 \mu U_c(t_n) D_{c,t_n}}{2} \ln \left[\frac{D_{c,t_n}}{D_o} \right] \quad (5.21)$$

Equation(5.21) can then be rewritten as:

$$\Delta P_{c,t_n} = \frac{k_2 \mu U_o D_o}{2} \ln \left[1 + \frac{\Delta x_{t_n}}{D_o} \right] \quad (5.22)$$

Total pressure is then rewritten as:

$$\Delta P_{total} = \Delta P_f + \Delta P_{c,t_n} \quad (5.23)$$

Further, filter and cake resistances are calculated using:

$$R = \frac{(P_o - P)}{\pi D_o U_{o,z}} = \frac{(P_o - P)}{\pi D_c U_{c,z}} \quad (5.24)$$

where $U_o(z)$ denotes the face velocity (i.e. at the outer diameter of the medium) at position z along the axis.

The pressure difference along the z –axis is:

$$\left[\frac{\pi^2 D_i^4}{32 \rho} \right] \frac{dP}{dz} = -Q(\pi D_c U_{c,z}) - \frac{f Q^2}{D_i} \quad (5.25)$$

and the cake thickness at position z is:

$$\Delta x = \frac{\Delta z}{L} \int \frac{w U_c(t)}{p_p (1 - \varepsilon_c)} dt \quad (5.26)$$

where L is the length of the candle.

CALCULATION OF CAKE RESISTANCE

Cake resistance can be calculated using the Carman-Kozeny equation, together with some assumptions (Chuah and Seville, 2004). Assuming that the cake is incompressible and that the particles are spheres that barely touch, then $S_o = 6/d_p$. The value of porosity of the cake is taken as 0.85. The porosity can be obtained experimentally. The calculated specific resistance values of the cake are shown in Figure 44.

As observed in Figure 44 the reduction in the cake resistance decreases as the particle size increases.

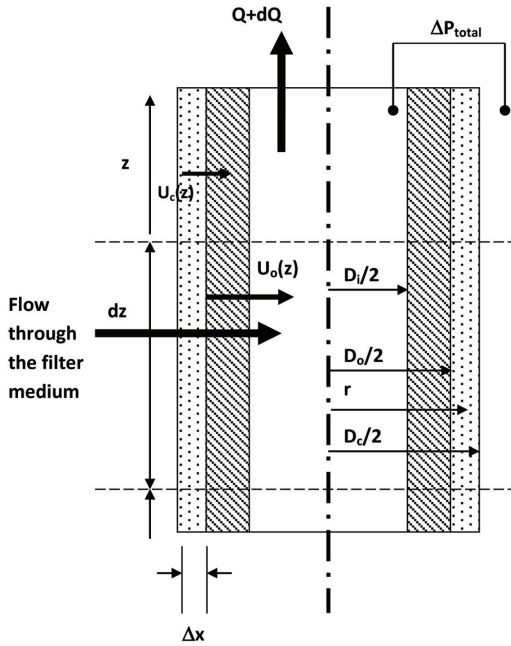


Figure 43 Schematic Diagram of Flow in a Filter Section with filter cake

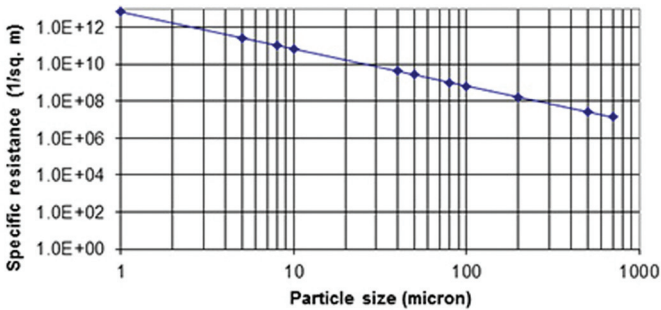


Figure 44 Relationship between particle size and the calculated cake resistance

CAKE POROSITY

The porosity of the filter cake is a very important parameter, as the pressure drop in the filter and the necessary force for the removal of the deposited dust layer depend on it. However, due to the high fragility of the dust cake, it is very difficult to measure experimentally. For a dust layer of thickness, L , composed of particles with mean diameter, d_p :

$$\frac{\Delta P}{L} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu U}{d_p^2} + 1.75 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{U^2}{d_p} \quad (5.27)$$

the mass of the particles deposited on the filter is calculated as:

$$M = \dot{m} t L A \rho_p (1 - \varepsilon) \quad (5.28)$$

where \dot{m} is the mass flow rate of particles of density, ρ_p , A is the filtration area and t is the filtration time. Therefore:

$$L = \frac{(Qt)}{[A \rho_p (1 - \varepsilon)]} \quad (5.29)$$

By substituting Equation (5.29) into the Ergun equation (5.27), it becomes:

$$\frac{\Delta P}{t} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu Q U}{A \rho_p d_p^2} + 1.75 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho Q U^2}{A \rho_p d_p} \quad (5.30)$$

Equation (5.30) can then be used for estimating the cake porosity from a graph of ΔP vs. t .

CAKE DETACHMENT AND PRESSURE DROP ANALYSIS

The dust cake is assumed to become detached from the filter medium when it experiences a tensile stress sufficient to overcome the strength of the adhesive bond between the cake and the medium

(or a residual dust layer). In theory, as soon as the strength is exceeded, the cake will be detached simultaneously from the filter surface. However, in practice, the adhesive strength and the applied stress is not entirely uniform across the filter surface, resulting in “patchy” cleaning.

In a rigid ceramic filter, the cleaning mechanism is different from that for the fabric filter. There is no displacement on cleaning, therefore, the tensile stress is entirely the result of the pressure drop imposed across the cake due to the reverse flow of cleaning gas. The range of tensile stress over which the cake detaches from the filter medium can be determined using a small flat “coupon” of filter medium. Results from the coupon test are then plotted in the form of “percentage cake remaining” versus “applied stress”, where the applied stress is the appropriate value of the pressure drop across the cake. The curve provides the information needed for the selection of a cleaning pressure.

Figure 45 shows an example of such a curve that might be used in practice. On the left-hand side is a set of cake detachment curves and on the right an imaginary axial distribution of cleaning pressure. If the measured cake detachment stress curve is ‘a’, then most of the cake will be removed from the pulse while if it is ‘c’, then very little will.

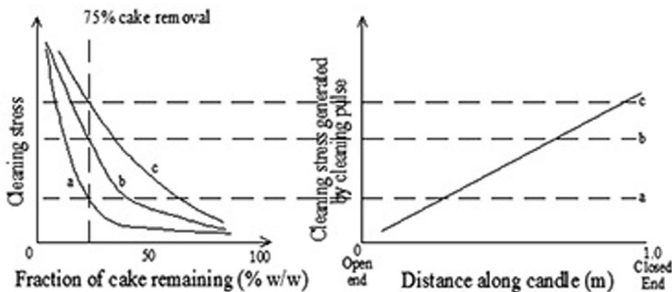


Figure 45 Variation of cake removal with axial position on candle

ADHESION FORCES AND CAKE DETACHMENT STRESS

At present, it is not easy to predict the stress which must be imposed on the filter medium to remove the deposited dust cake. An agglomerate of spherical particles would break if the separation force imposed on the particles by a normal tension is larger than the force of adhesion that keeps the particles together. Thus, rupture of the agglomerate occurs with the simultaneous breaking of the connections amongst the particles, in a certain plane through it. Rumpf calculated the tensile strength of a particle compact by summing the strengths of the particle-particle contacts which must be broken across the failure surface. The agglomerate strength expression is written as:

$$\sigma = \pi \frac{(1 - \varepsilon)}{\varepsilon} \frac{\gamma_s}{d_p} \quad (5.30)$$

where γ_s is the particle surface energy, d_p is the particle diameter and ε is the void fraction. The expression σ was then modified as:

$$\sigma = n_c F_{ad} \quad (5.31)$$

where F_{ad} is the force of adhesion between two particles and n_c is the average number of particleparticle contacts per unit area:

$$n_c = 1.1(1 - \varepsilon) \varepsilon^{-1} d_p^{-2} \quad (5.32)$$

In the case of dry and inert agglomerates, without the presence of binders or electrostatic charges, the forces of adhesion between the particles are usually due to Van der Waals interactions. For two spheres of the same diameter, d_p , the force can be described as:

$$F_{ad} = \frac{H d_p}{(24 a^2)} \quad (5.33)$$

where H is the Hamaker constant, which depends on the particle composition (and has a value of around 8×10^{-20} J, for most materials of interest, and a is the distance of separation between the surfaces of the particles. The cake removal stress can then be written as:

$$\sigma = 0.046 \frac{(1-\varepsilon)H}{\varepsilon d_p} \frac{1}{a^2} \quad (5.34)$$

Figure 46 shows the relationship between the cake removal stress and the particle diameter and porosity of the filter cake using Rumpf's agglomerate strength expression. It can be seen that as the particle size increases the cake removal stress decreases, as predicted by all available theories.

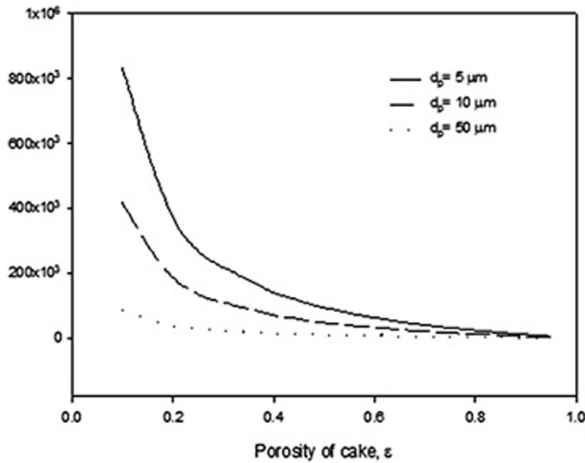


Figure 46 Dependence of cake removal stress on the particle diameter and cake porosity with fitted value of γ_s for limestone

For reverse flow cleaning, the prime interest in investigating the cake removal characteristics of a given dust-medium combination should comprise both the contribution from the cake and the filter medium and is written as:

$$\Delta P_c = \Delta P_T \left[\frac{R_c}{R_c + R_m} \right] \quad (5.35)$$

where P_T is total pressure drop across the filter medium and cake and R_c and R_m are modified resistance for the cake and filter medium, respectively.

RESULTS OF SAMPLE CALCULATIONS

A large number of sample calculations were made to ensure that the procedures outlined above were valid and workable. Some of the results obtained are presented in the following sections. The conditions used for the calculations are outlined in Table 8. The physical dimensions used here were taken from the previous pilot plant study. Further, the carrier gas, air, was taken to be incompressible over the pressure range of interest.

Table 8 Parameters used in simulations

Length of filter, L (m)	1	Resistance to flow, R (Ns/m ⁴)	22290 (open end) 43120 (closed end)
Inner diameter, D _i (m)	0.042m	Particle density, Limestone, ρ_p (kgm ⁻³)	2500
External diameter, D _o (m)	0.062	Dust concentration, w (kgm ⁻³)	0.01026
Gas viscosity, μ (kgm ⁻¹ s ⁻¹)	1.7894 x 10 ⁻⁵	Cake porosity, ε	0.85
Gas density, ρ_g (kgm ⁻³)	1.225	Time interval, Δt (s)	300

As discussed previously, the method developed enables one to calculate the total pressure across the filter medium and filter cake. The thickness of the filter cake which forms on the surface of the medium for a given face velocity, with a constant particle concentration, can also be calculated. The concentration w is directly proportional to the total amount of particles to which the filter media is exposed and is the independent variable.

RELATIONSHIP OF DUST CONCENTRATION AND FACE VELOCITY

The properties of the dust cake formed during filtration depend mainly on the filter face velocity, the filter medium, gas temperature and, in particular, the particle properties. An essential feature is the pressure drop in connection with the permeation of the dust cake.

The pressure drop across the cake, ΔP_c , depends on the dust concentration and the face velocity. As ΔP_c increases with time, it is more appropriate to use the rate of increase of the pressure drop, $d\Delta P_c/dt$, to express the influence of these factors. By solving the equations described earlier, which enable the calculation of the pressure drop across the filter cake for the whole filter (i.e. for $z = 0$ to L), the relationships between the rate of increase of the pressure drop, the dust concentration and the face velocity are plotted individually.

Figure 5.8, which shows the relationship between the rate of increase of the pressure drop (from the simulation) and the dust concentration under ambient conditions, confirms, as expected, that $d\Delta P_c/dt$ is proportional to the dust concentration.

Figure 5.9 shows the relationship between $d\Delta P_c/dt$ and the face velocity. $d\Delta P_c/dt$ (from the simulation) is proportional to the second power of the face velocity, which follows directly from the Carman-Kozeny equation, which can be rewritten as:

Rigid Ceramic Filters

$$\frac{\Delta P}{dL} = \frac{(1-\varepsilon)^2 S_o^2}{\varepsilon^3} \mu u \quad (5.36)$$

Therefore, for constant dust concentration,

$$\frac{d\Delta P}{dt} = \frac{(1-\varepsilon)^2 S_o^2}{\varepsilon^3} \mu u^2 \quad (5.37)$$

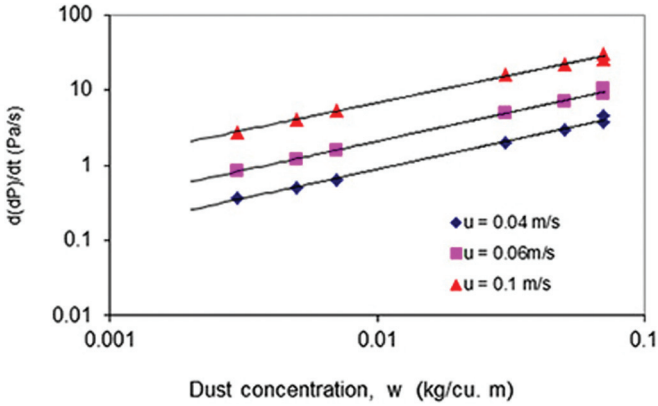


Figure 47 Relationship between the pressure drop increase rates and the dust concentration under ambient conditions

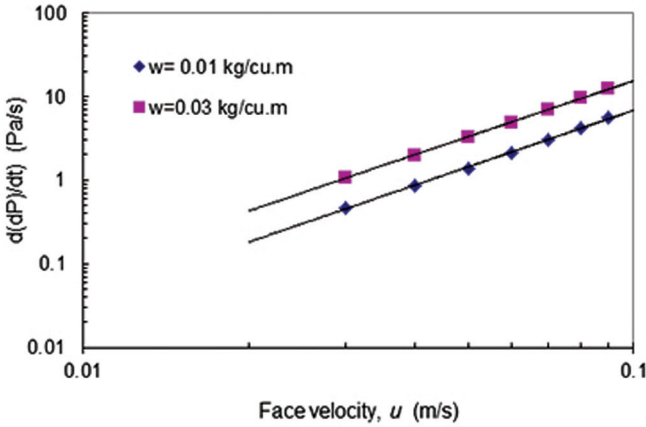


Figure 48 Relationship between the pressure drop increase rates and the face velocity under ambient conditions

EFFECT OF REVERSE FLOW VOLUMETRIC FLOW RATE

The distributions of dust cake thickness with varying reverse volumetric flow rates are shown in Figure 49 (face velocities 4 cm/s) and Figure 5.11 (face velocities 6 cm/s). As can be seen in these figures, the dust cakes remained in the area near the open end, because the applied stress was lower than the detachment stress of the dust cake in that region. Higher volumetric cleaning flow rates will thus improve the cleaning of the filter. However, even at the highest flow rate some fraction of the dust cake will still remains on the filter. Detachment of the filter cake occurs more readily at the bottom of the candle because that is where the applied detachment stress is the highest.

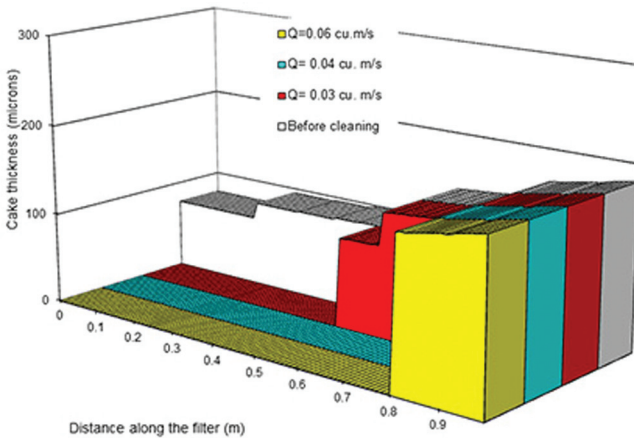


Figure 49 Cake detachment after reverse flow cleaning with a face velocity of 4cm/s

Rigid Ceramic Filters

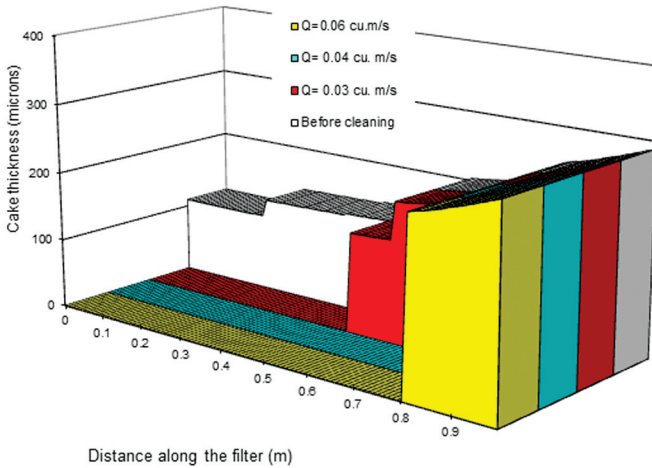


Figure 50 Cake detachment after reverse flow cleaning with a face velocity of 6 cm/s

CONDITIONING OF THE FILTER

Figure 5.1 shows the pressure difference profile before cleaning and after the first cleaning cycle. It shows that the pressure drop was reduced in the area where the dust cake had been removed. However, the pressure drop was increased close to the open end due to the fraction of uncleaned dust cake remaining. Now “younger” dust cake will be deposited on top of the older filter cake layer thereby increasing the pressure drop.

Using the numerical model, the pressure drop was simulated as a function of time in order to analyse the filter conditioning (Luqman Chuah, 2014). Figure 52 shows the simulated pressure difference history for the first five cycles of the filtration with a face velocity of 4 cm/s. The filter was cleaned when the pressure reached 400 Pa. The non linear curve indicates that non-homogeneous cake cleaning occurred throughout the filtration. However, there was not much difference between successive filtration cycles.

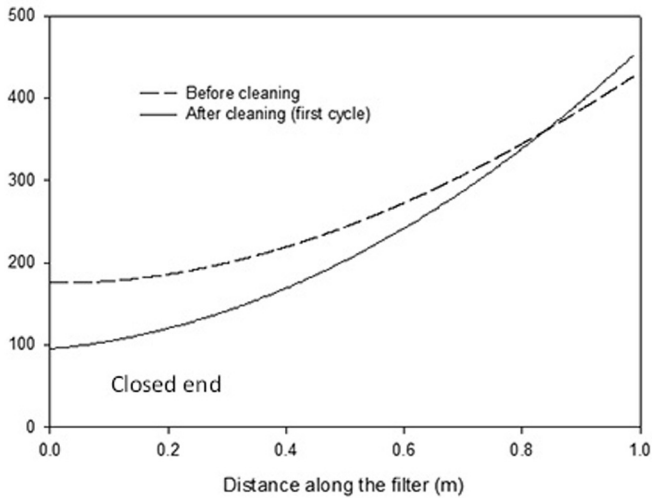


Figure 51 Pressure difference distribution before and after first cycle of cleaning in filtration mode

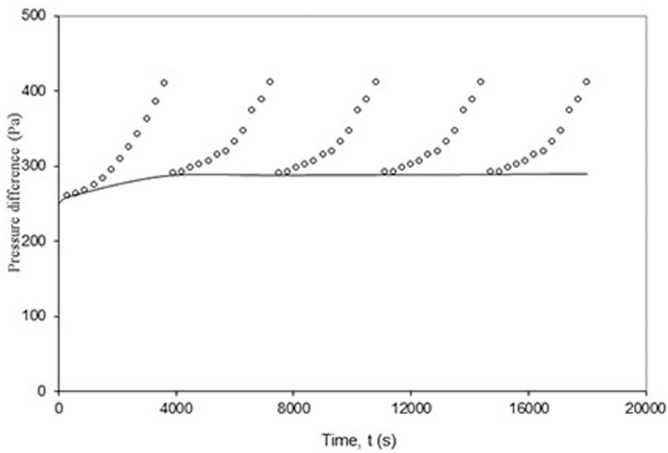


Figure 52 Simulated pressure difference vs. filtration time for a sequence of filtration cycles (4 cm/s)

CONCLUSIONS

The origin of non-uniformity in pressure difference across the wall, in both the filtration and cleaning modes, is the internal (axial) pressure drop due to (a) axial momentum changes caused by flow through the wall and (b) wall friction. Both these effects can be reduced by reducing the axial gas velocity, which obviously has the highest value towards the open end (in both filtration and cleaning modes). This can be done by tapering the filter from the open to the closed end. 3 mathematical models were developed. These were a Computational Fluid Dynamics (CFD) model, a Simple Excel Reverse Pulse Flow Model and a time-dependent filter cake build-up model. The CFD technique was applied to the simulation and analysis of fluid flow in rigid ceramic filters. This method offered a general technique for predicting the gas flow in the filter, modelled by the Navier-Stokes equations, whilst the flow through the porous region was described by the Darcy equation. The simulation results were in fair agreement with the experimental results, demonstrating that CFD packages are able to predict pressure distributions inside candles with reasonable accuracy.

A mathematical model written in Excel provided a simple, quick and the acceptable prediction of the pressure distribution in the filters. The model was able to predict the pressure drop and the velocity profile along with a filter element during reverse flow cleaning. Both modelling and experimental results suggested that a more uniform pressure distribution was achieved in the tapered elements. The simulations showed that the separation distance of the pulse tube from the candle neck has an effect on the pressure distribution. The greater the distance of the pulse tube from the filter the greater the pressure difference in the filter. This was due to the large volumetric gas flow that was converted into gas momentum and contributed to the pressure difference across the filter wall. At

larger distances, the increment in the pressure difference became less significant.

The simulation also revealed that at higher friction factor, the pressure difference across the filter wall did not decrease continuously; it passed through a minimum before the closed end was reached. As the gas flow travelled along the filter from the open end to the closed end of the filter, the pressure drop caused by friction was reduced because the volumetric flow is then small and made little contribution to the pressure difference across the wall. The axial velocity was recovered as static head, thus increasing the pressure difference across the wall. Increasing temperature will increase the gas viscosity in the filter cavity and thus, the pressure drop across the filter wall will be greater. However, the gas density also decreases with increasing temperature and hence reduces the pressure difference along the filter candle. So, the combination of these effects makes the pressure difference distribution more uniform.

Results from the cake build-up model give some idea of the conditioning process and the development of patchy cleaning of the filter surface. The residual layer left uncleaned after the reverse pulse cleaning forms a “patch” on the filter surface. Particles agglomerate on the remaining filter cake and so the pressure distribution becomes less homogenous and thus the overall filtration and cleaning efficiency are reduced. This is the result of the laying-down of a residual layer on and within the first millimeter of the surface and insufficient removal of the filter cake.

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BIOGRAPHY

Luqman Chuah started his career in the Department of Chemical and Environmental Engineering in 1996 and is currently a Professor in his department. He served as Head of Research Laboratory in the Institute of Tropical Forestry and Forest Products (INTROP) for 7 years and is currently Editor of INTROP's Bulletin, *INTROPICA*. He was appointed as Deputy Dean (Industrial Relationship and International), School of Graduate Studies, UPM from year 2011 until 2014.

Luqman Chuah's research areas involve chemical engineering (Separation Technology and Particle Technology), environmental engineering (Air Pollution and gas Cleaning, Wastewater Treatment), material engineering (Nanomaterials and Biopolymers) and pytochemical processing (Extraction and Drying Technology). He also managed to secure several national and international research grants, which include the "CNG/DI Engine and Transmission" project with value of RM28 million from MOSTI, "Increased Production Efficiency in Small-holder Kenaf Production Systems for Specific Industrial Applications", a UNIDO project with USD 2 million and "Kenaf Upstream and Downstream Research, RM5 million, supported by the Economic Planning Unit (EPU) etc. In 2007, he was awarded another project related to biopolymer with RM3 million by the Ministry of Higher Education, Malaysia-HICOE Tropical Wood And Fibre Research Centre and Institute of Tropical Forestry and Forest Products (INTROP), UPM. He has also developed a strong research network with other research institutions, such as the Malaysian Palm Oil Board (MPOB), Malaysian Nuclear Agency, Forest Research Institute Malaysia (FRIM), Malaysia Rubber Board (MRB), Malaysia Timber Industry Board (MTIB) and other higher educational institutions.

He has contributed greatly to human capital development. He is currently supervising 13 PhD and 4 Master students while 24 Master and 14 PhD students have already graduated under his supervision. Further, Luqman Chuah has published more than 500 publications, including 249 articles in referred journals, proceedings, books and technical articles.

He also serves as the editorial member of several journals and owns 12 intellectual properties of patents and industrial design. He is also serving as editorial member of various local and international journals.

Luqman Chuah is actively involved in professional bodies' activities. He was a committee member in the Chemical Engineering Technical Division, Institution of Engineers Malaysia (IEM), 2005-2008. He was an active member and in charge of organizing talks and visits. He is also a committee member of the Publication Standing Committee, the IEM Library Chairman and was the Bulletin and IEM Journal editorial member for the period 2005-2009. Luqman Chuah is also a member of many other professional bodies. These include the Royal Academy of Science International Trust, Tunisia, Professional member of the Institute of Materials, Malaysia, Member of the Institute of Chemical Engineers, UK (IChemE), Life member of the Malaysian Oil Scientists' and Technologists' Association and the Malaysian Water Association. Further, Luqman Chuah has also been serving as an assessor for the Malaysia Qualification Agency (MQA) to evaluate programs of IPTAs and IPTSs from 2008 until now. He has also been invited as the keynote speaker and forum panel member for several international and national events and companies.

Luqman Chuah has won several awards in teaching, service and research, e.g., Award of Excellent Teaching, 5Stars Supervisor, ITEx, MTE, BIS and Eureka. Luqman Chuah also won the IEM Young Engineer Award for his excellent contributions to the field of engineering and research in the nation in 2006. Additionally, he was awarded the Raja Tan Sri Zainal Prize for Best Technical Paper (2006) and Ir. Thean Lip Thong Prize for Best Technical Paper Award (2008). In year 2013, he was awarded the Top Research Scientists Malaysia (TRSM) award by Academy of Sciences Malaysia (ASM). Furthermore, he was awarded the Malaysia Rising Star Award by the Ministry of Higher Education Malaysia and was recognized as one of the Top 1% Globally Cited Researchers by Thomson Reuters in the year 2015.

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- My wife, Zainorhayati binti Zainudiin, the lady of my life, thanks a lot for your support and courage and the happiness that you bring to me, with love.
- To my children, for their undivided love.

I would like to thank those who have contributed to the work which has gone into this, either through discussions or experimentation. Finally, I would like to thank all my friends for their motivation, support and friendship over the years. Thank you all.

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